# In-Flight Operation of the Dawn Ion Propulsion System Through Completion of the Final Orbit Around Dwarf Planet Ceres

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**The Dawn mission, part of NASA's Discovery Program, has as its goal the scientific exploration of the two most massive main-belt objects, Vesta and Ceres. The Dawn spacecraft was launched from the Cape Canaveral Air Force Station on September 27, 2007 on a Delta-II 7925H- 9.5 (Delta-II Heavy) rocket that placed the 1218-kg spacecraft onto an Earth-escape trajectory. On-board the spacecraft is an ion propulsion system (IPS) developed at the Jet Propulsion Laboratory for the heliocentric transfer to Vesta, orbit capture at Vesta, transfer between Vesta science orbits, departure and escape from Vesta, heliocentric transfer to Ceres, orbit capture at Ceres, transfer between Ceres science orbits, and orbit maintenance maneuvers. Full-power thrusting from December 2007 through October 2008 was used to successfully target a Mars gravity assist flyby in February 2009 that provided an additional ΔV of 2.6 km/s. Deterministic thrusting for the heliocentric transfer to Vesta resumed in June 2009 and concluded with orbit capture at Vesta on July 16, 2011. From July 2011 through September 2012 the IPS was used to transfer to all the different science orbits at Vesta and to escape from Vesta orbit. Cruise for a rendezvous with Ceres began in August 2012 and completed in late December 2014. From December 2014 through June 2016 the IPS was used for transiting the spacecraft to all science orbits at Ceres including the final orbit for Dawn's primary mission, called the low altitude mapping orbit (LAMO), a circular orbit at a mean altitude above Ceres of approximately 385 km. Dawn met or exceeded all pre-launch science requirements and Dawn's prime mission concluded on June 30, 2016. Dawn subsequently received NASA approval for two extended missions at Ceres, called XM1 and XM2. During XM1 IPS was used for orbit maintenance and to transit the spacecraft to several new, higher-altitude science orbits, ending in an elliptical orbit at a maximum altitude of approximately 38,000 km. In XM2, IPS operations included transiting the Dawn spacecraft to its final, highly elliptical orbit at Ceres ranging from 35 km perigee to 4,800 km apogee. Science data acquisition will continue in XM2 until the hydrazine is exhausted, which is expected to occur between August and October 2018. Dawn has successfully completed all science goals for both the primary and XM1 extended missions. To date the IPS has been operated for approximately 51,250 hours, consumed approximately 416 kg of xenon, and provided a delta-V of almost 11.5 km/s, a record for an on-board propulsion system. The IPS performance characteristics are close to the expected performance based on analysis and testing performed pre-launch. Dawn's IPS continues to be fully operational as of June 2018. This paper provides an overview of Dawn's mission objectives and the results of Dawn IPS mission operations for XM1, and XM2 through June 2018.**

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# I. Introduction

Missions using electric propulsion have attained a high level of success and reliability of operation. In the past 10 years alone there have been approximately 90 spacecraft launched successfully using electric propulsion for attitude control, orbit raising, station keeping and for primary propulsion, with 20 spacecraft using electric propulsion launched in 2017[1]. Deep Space 1 (DS1), the first interplanetary mission to use ion propulsion, operated its single thruster ion propulsion system for over 16,000 hours before successfully completing its primary and extended missions [2]. Approximately 200 ion thrusters (13-cm-dia and 25-cm-dia) built at L3 Technologies, Torrance, CA are aboard 50 communication satellites built by Boeing Defense, Space and Security for orbit-raising and station-keeping functions, accumulating ~600,000 operating hours in flight [3]. In 2013 there were approximately 156 operational spacecraft flying electric propulsion systems built by Aerojet Rocketdyne[4].

The Dawn mission is the ninth project in NASA's Discovery Program. The goal of the Discovery Program is to achieve important space science by launching regular smaller missions using fewer resources and shorter development times than past projects with comparable objectives [5]. The combination of low-cost and short development times presents substantial challenges to an ambitious mission such as Dawn. The Dawn mission is led by the principal investigator, Dr. Carol Raymond, from the California Institute of Technology-Jet Propulsion Laboratory (JPL), in Pasadena, CA, and the mission is managed for NASA by JPL.

The Dawn mission has as its goal the scientific exploration of the two most massive main-belt objects, Vesta and the dwarf planet Ceres, for clues about the formation and evolution of the early solar system. Vesta is the second most massive main belt object with a mean diameter of 530 km. Ceres, with a diameter of 950 km, is the largest and most massive body in the asteroid belt. Ceres is classified as one of five dwarf planets in our solar system, and studies suggest it may have a large inventory of subsurface water. The science underlying the Dawn mission is described in [6,7]. To realize these science goals the Dawn spacecraft rendezvoused with and orbited each body. Dawn is the first mission to orbit a main belt object and the first to orbit two extraterrestrial targets. The Dawn mission is enabled by a three-engine ion propulsion system (IPS) that provided most of the velocity change needed for heliocentric transfer to Vesta and Ceres, orbit capture at Vesta and Ceres, transfer to Vesta science orbits and orbit maintenance, orbit escape and departure from Vesta, and transfer to science orbits and orbit maintenance at Ceres. Without ion propulsion, a mission to orbit Vesta alone would have been unaffordable within NASA's Discovery Program, and a mission to orbit both Vesta and Ceres would have been impossible with a single launch.

The Dawn spacecraft was launched from Cape Canaveral Air Force Station on September 27, 2007. The first 80 days of the mission were dedicated to a comprehensive spacecraft and IPS checkout [8]. Cruise operations for deterministic thrusting began December 18, 2007 leading to a Mars flyby in February 2009, and rendezvous and orbit capture at Vesta on July 16, 2011, with a science phase lasting approximately 13 months [9]. At the conclusion of the Vesta science phase in July 2012 the Dawn spacecraft departed Vesta for deterministic thrusting to Ceres, leading to orbit capture at Ceres on March 6, 2015. Over the next 3.3 years the IPS was used for all orbit maneuvers at Ceres to enable scientific study of this proto-planet. Dawn completed all of its its science objectives and its primary mission ended on June 30, 2016. Dawn began an extended mission at Ceres on July 1, 2016, and in October 2017, following a successful 16-month science campaign, Dawn was approved for a second extended mission. The final orbital maneuver at Ceres made use of Dawn's IPS to transit the spacecraft to its final science orbit, placing the spacecraft into a highly elliptical but very stable orbit with a periapsis altitude above Ceres of 35 km and an apoapsis altitude of approximately 4,000 km. The final science phase began on June 8, 2018 and Dawn will continue conducting scientific studies of Ceres until sometime between August-October 2018, when the hydrazine on-board the spacecraft is exhausted and spacecraft attitude control is lost, ending the mission. This paper presents a summary of the Dawn IPS mission operations from start of ion thrusting for cruise to Vesta through the completion of ion thrusting in XM2.

# II. MISSION AND SYSTEM FLIGHT OVERVIEW

The mission and flight system are described in detail in [10,11], and are summarized here. A schematic diagram of the Dawn flight system is shown in Figure 1, with a mass summary for the Dawn flight system in

Table 1. JPL was responsible for the high voltage electronics assembly (HVEA) and science payload development, IPS development and development of other spacecraft components, safety and mission assurance, project systems engineering, mission design, and navigation development, and is responsible for mission operations system development and mission operations which are conducted from JPL.

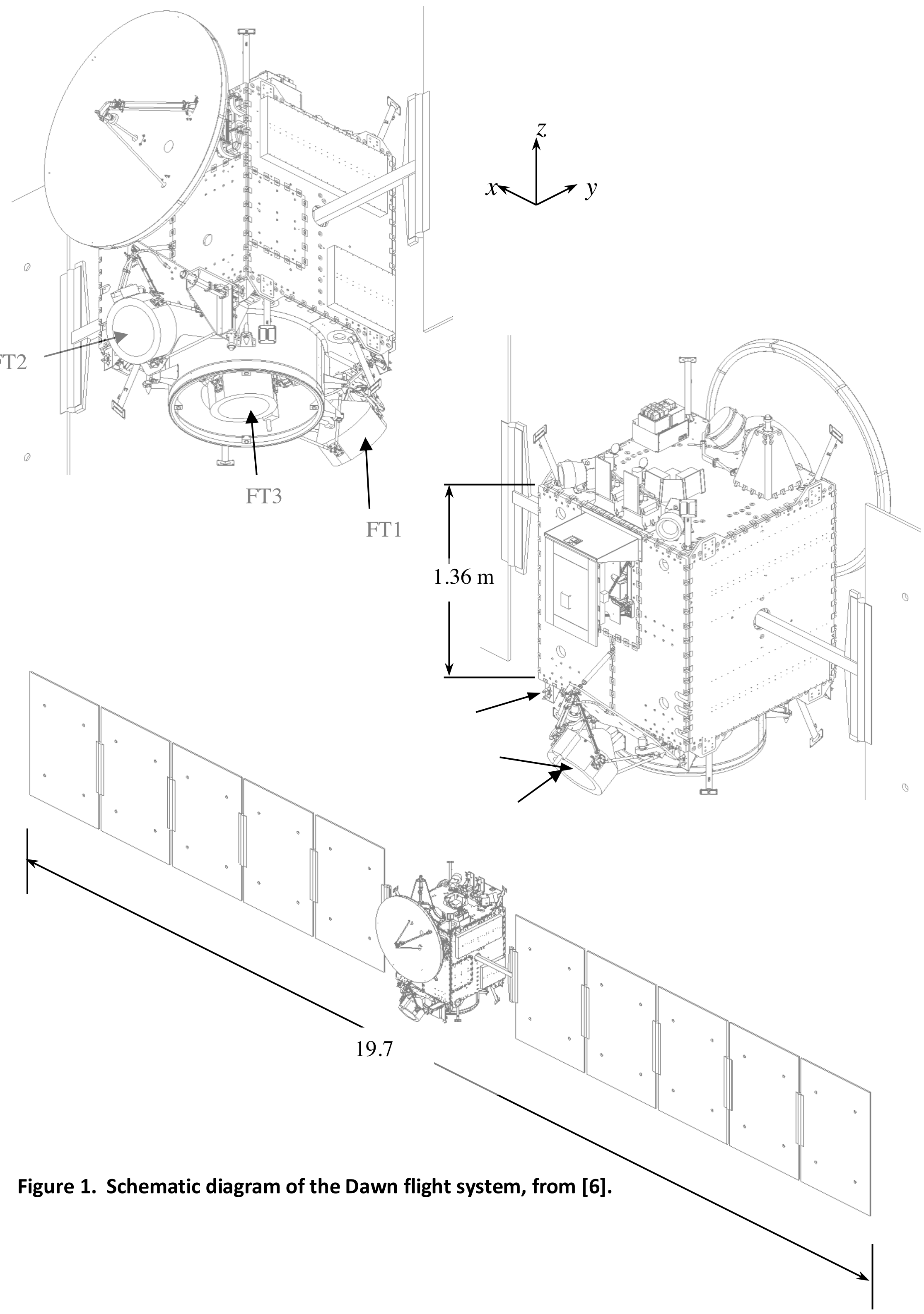


**Figure 1. Schematic diagram of the Dawn flight system, from [6].**

Orbital ATK (Orbital), Sterling, VA, was responsible for developing the spacecraft bus, flight system integration and testing, and launch operations. The spacecraft is based on Orbital's GEOStar-2 [12] satellite platform series. The solar array (SA) consists of two large panel assemblies approximately 18 $m^2$ each and measuring almost 20 m tip to tip with triple junction cells providing more than 10 kW of electrical power at one astronomical unit (AU) and 1.3 kW for operations at Ceres. Articulation of the solar arrays is about the Y-axis. The spacecraft attitude control subsystem (ACS) employs four reaction wheel assemblies (RWA) for three-axis control of the spacecraft and makes use of the IPS for pitch and yaw control during normal IPS thrusting. The reaction control subsystem (RCS) uses hydrazine thrusters for direct three axis control of the spacecraft and was intended primarily for desaturating the reaction wheels. The spacecraft launched with 45 kg of hydrazine on-board for RCS use on this 11-year-long mission. Three of the four RWAs failed [13], so conservation of hydrazine was very important, but Dawn met its science goals for Vesta and Ceres through a hybrid RWA/ACS spacecraft control architecture[13].

**Table 1. Dawn Flight System Mass at Launch**

| Description | Mass, kg |
|---|---|
| Dry spacecraft and avionics (except IPS) | 573 |
| Science instruments | 46 |
| Hydrazine | 45 |
| Ion Propulsion System (IPS) | 129 |
| Xenon | 425 |
| **Flight system mass at launch** | **1218** |

The Dawn ion propulsion subsystem (IPS) developed at JPL is described in detail in [11] and is shown in the block diagram in Figure 2. The IPS is single-fault tolerant as configured for Dawn and is based on the single-engine ion propulsion system flown successfully on the DS1 mission [2], but modified for multiple thrusters and supporting hardware. The Dawn IPS includes three 30-cm-diameter xenon ion thrusters operated one at a time, two power processor units (PPU), two digital control interface units (DCIU), three Thruster-Gimbal Assemblies (TGA) for two-axis thrust-vector control, a Xenon Control Assembly (XCA) for controlling xenon flow to the engines, and a single xenon storage tank. The ion thrusters and the PPUs are based on technology developed by NASA Glenn Research Center (GRC), and engineered and fabricated for flight by L-3 Technologies Electron Devices Division Inc., Torrance, CA, with minimal modifications to their designs from DS1.

The two DCIUs, which accept commands from the spacecraft, command the PPU supplies, operate the valves on the XCA and actuators on the TGAs, return IPS telemetry and serve as a pass-through for spacecraft commands to the TGAs, were designed and fabricated at JPL. The design was modified from the DS1 design to meet the multi-engine system functionality and cross-strapping required for Dawn. Each DCIU interfaces to a single PPU, to the XCA components and xenon high pressure subassembly, and to each of the three TGAs. Each DCIU provides low voltage power to its corresponding PPU. Only one DCIU is powered up and operated at a time and the unused DCIU is left in an unpowered state. The DCIUs include software needed for automatic and autonomous control of IPS including thruster power levels, flow system valve actuation, and XCA flow control settings. Both DCIUs are mounted next to the PPUs to the same thermally-controlled plate within the core structure of the spacecraft.

The Dawn ion propulsion system is designed to be single-fault-tolerant. Ion thrusters using the 30-cm-diameter NASA design were operated for 16,265 hours on the DS1 mission [2] and 30,352 hours in an extended life test [14], however the Dawn mission required 401 kg (Table 2, xenon allocation summary) or approximately 200 kg per ion thruster if one thruster fails at the beginning of the mission. To accomplish the mission at least two ion thrusters, two TGAs, one PPU, and one DCIU had be fully functional throughout the mission [11]. Analyses [15] and flight data [16] indicate that a two-engine IPS can perform the Dawn mission with a low risk of failure due to ion thruster wear if the thrusters and PPUs are cross-strapped as shown in Figure 2 such that the loss of one thruster or PPU does not impact successful operation of the remaining two ion thrusters or PPU. Each PPU is connected to one DCIU and directly to the HVEA which provides unregulated solar array power to the PPUs. FT3 can be powered by either of the two PPUs, while FT1 is connected only to PPU-1 and FT2 is connected only to PPU-2. The high voltage harnesses connecting the

PPUs to the ion thrusters appear as the red lines in Figure 2. Only one of the PPUs is powered on at any time, and the unused PPU is left in an unpowered state. The mission trajectory used for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below.

The center-mounted thruster is designated FT3 (flight thruster 3), and can be powered by either PPU. The outboard thrusters are designated FT1 on the –X panel and FT2 on the +X panel. Each thruster is mounted to a TGA with two struts to each thruster gimbal pad in a hexapod-type configuration (six struts total per ion thruster). Actuators driven by electronics cards in the DCIU that are commanded by the spacecraft ACS are used to articulate two of the three TGA struts for 2- axis control of the thrust pointing vector through the spacecraft center of mass and to provide pitch and yaw control during ion thrusting.

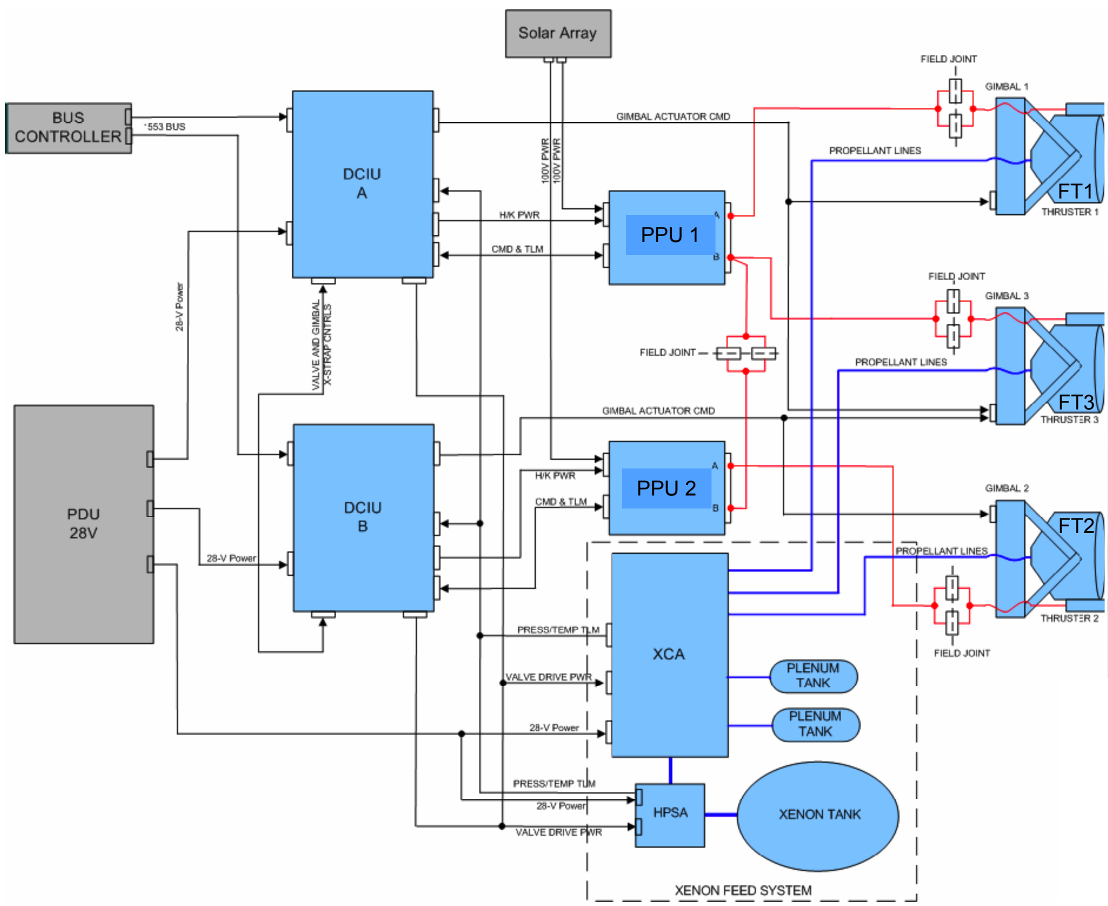


**Figure 2. Simplified block diagram of the Dawn IPS.**

A titanium-lined composite-overwrap xenon tank developed for Dawn with a volume of 269 liters was mounted inside the core structure of the spacecraft and loaded with 425 kg of xenon prior to launch, with a xenon storage density at launch of approximately 1.6 g/cm3. The ratio of tank mass to xenon mass is 0.05 and represents a true breakthrough in total IPS mass reduction. The xenon feed system is based on the DS1 design but was modified to operate multiple thrusters and to be single-fault tolerant. It includes the XCA placed outside the spacecraft core cylinder with two 3.7-liter plenum tanks identical to those flown on DS1, and uses the same xenon flow rate control design to control pressure to flow rate control devices (flow orifices), latch valves and solenoid valves (similar to those used on DS1), service valves, interconnecting tubing, and nine flexible propellant lines (three for each thruster across the TGA interface). The flow orifices were carefully calibrated pre-flight for flow rate determination based on pressure and temperature at the flow orifices. Total xenon consumption is calculated by integrating the pressure and temperature at the flow orifices. A different method for calculating total xenon consumption makes use of the xenon storage tank pressure and estimates of the bulk xenon temperature. A third method uses solenoid valve cycling characteristics to estimate the pressure in the xenon storage tank. The three methods agree to within approximately 6 kg, or approximately 1.5 percent of the total xenon used. In Table 2 and throughout this paper the xenon consumption is based on the flow control device (FCD) calibrations.

The mission trajectory for Dawn is shown in Figure 3, and a list of important mission phases is summarized in Table 3 below. The post-launch ΔV, from the initial checkout through conclusion of Ceres science operations and including the Mars gravity assist, was approximately 14.1 km/s (Table 3). The IPS provided 11.5 km/s of this ΔV and used approximately 416.6 kg of xenon for the complete mission.

**Table 2. Xenon Allocation Summary (Actuals from FCD Model)**

| Description | | Xenon Allocation (kg) |
|---|---|---|
| Initial Checkout | Actuals | 3.1 |
| Deterministic Thrusting To Vesta | Actuals | 246.0 |
| Vesta Operations | Actuals | 10.3 |
| Deterministic Thrusting To Ceres | Actuals | 117.9 |
| Ceres Operations | Actuals | 39.3 |
| Total Xenon Used In Flight | Actuals | 416.6 |
| Main Tank Residuals | | 6.0 |
| Margin | | 2.6 |
| Total | | 425.2 |

Figure 3. Dawn mission trajectory.

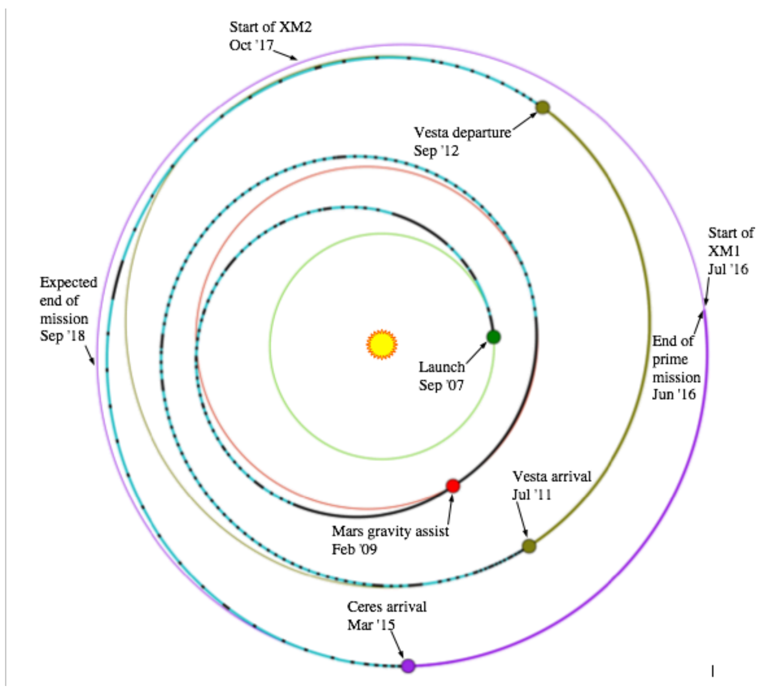


Table 3. Dawn Mission Summary. Bold font indicates the mission phase has been completed.

| Description | Time Period | Distance S/C to Sun ( AU ) | Power Level To IPS ( kW ) | Comments |
|---|---|---|---|---|
| Launch | 09/27/2007 | 1.0 | NA | |
| Initial Check-out | 09/2007 - 12/2007 | 1.0 - 1.16 | 2.6 | ΔV = 0.1 km/s |
| Cruise prior to MGA | 12/2007 - 11/2008 | 1.16 - 1.40 | 2.6 | ΔV = 1.8 km/s |
| Optimal Coast and Mars Gravity Assist (MGA) | 11/2008 - 06/2009 | 1.40 - 1.60 | NA | ΔV = 2.6 km/s (From MGA) |
| Cruise to Vesta | 06/2009 - 07/2011 | 1.40 - 2.26 | 2.6 -1.7 | ΔV = 4.8 km/s * |
| IPS Operations at Vesta | 07/2011 - 09/2012 | 2.26 - 2.53 | 1.7 -1.3 | ΔV = 0.3 km/s |
| Cruise to Ceres and Approach | 09/2012 - 04/2015 | 2.51 - 2.84 | 1.3 -0.9 | ΔV = 3.9 km/s ** |
| Ceres Science Operations | 04/2015 – 07/2018 | 2.84 - 2.98 | 0.4-0.6 | ΔV = 0.7 km/s |
| Total From IPS | | | | ΔV = 11.5 km/s |
| Mission Total | | | | ΔV = 14.1 km/s |

* From start of cruise to orbit capture at Vesta
** From start of cruise to Ceres to the first science orbit at Ceres (RC3)

## III. Overview of IPS Operations and Performance at Ceres

### Science Overview for XM1 and XM2

Dawn's prime mission, which concluded on June 30, 2016, met or exceeded all of the prelaunch requirements for science data acquisition at both Vesta and Ceres. Indeed, Dawn accomplished objectives at Ceres not even conceived until after two reaction wheels had failed.

At the conclusion of Dawn's primary mission the spacecraft and IPS were fully operational, with the exception of the RWA failures noted previously. NASA evaluated several options and in June 2016 approved Dawn for its first extended mission at Ceres, called XM1. Dawn XM1 science operations are described in detail by Rayman [13], and summarized here.

At the start of XM1 Dawn had used most but not all of its propellent consumables, with approximately 11.6 kg of the original load of 45.3 kg of hydrazine remaining. Of the 425.2 kg of xenon loaded, 24.3 kg remained, based on the FCD model. As described in [13], with the loss of two RWAs, hydrazine consumption became the major driver for mission operating life. During non-IPS thrusting periods the Dawn spacecraft operates in a dual RCS-RWA hybrid mode to control spacecraft attitude, which minimizes hydrazine consumption. Mission designs were developed to perform the science while simultaneously minimizing hydrazine consumption rates.

Dawn continued acquiring new science data in the circular low altitude mapping orbit (LAMO) at 385 km altitude. When XM1 began on July 1, 2016, the orbit was designated extended mission orbit 1, or XMO1. The highest priority for XM1 was to improve the signal-to-noise ratio of the gamma ray spectra and neutron spectra obtained by the Gamma Ray and Neutron detector (GRAND). With only two operable reaction wheels, the rate of hydrazine use for attitude control in XMO1 was so high that the mission lifetime was very limited, especially considering the risk of a third wheel failure. Analysis showed that the remaining hydrazine would be better spent reducing the GRAND instrument noise, caused principally by cosmic rays from reflected from the surface of Ceres. To do so, Dawn needed to transfer to a high altitude, where the signal from Ceres was negligible, so the cosmic ray background could be better characterized with the instrument settings that were used for the LAMO/XMO1 nuclear spectra.

From Sept. 2, 2016 to Oct. 6, 2016, Dawn used the IPS to transfer to XMO2, which, at about 1,480 km, was close in altitude to HAMO. XMO2 was focused on acquiring new infrared spectra and new images of specific targets, but it also provided the opportunity to remap Ceres to search for changes in the 12 months since HAMO. For this and all subsequent IPS operations, during IPS thrusting the spacecraft pitch and yaw were controlled with the IPS, as noted previously in the section of this paper describing the IPS system, to reduce hydrazine consumption during maneuvers.

From Nov. 4, 2016, to Dec. 5, 2016, the IPS raised the orbit to XMO3, an elliptical orbit with a minimum altitude of 7,530 km. That was high enough that Dawn could make the required cosmic ray background measurements. At that altitude, hydrazine consumption was significantly lower than in LAMO/XMO1, thus allowing a longer period of measurements. Dawn also acquired more images and spectra of Ceres in XMO3.

As the only requirement for the background measurements was that Dawn collect data from above 7,200 km over Ceres, a new XM1 objective was added. Thanks to the capability of the IPS, it was recognized that Dawn could shift its orbit plane by about 90° to observe Ceres at a Sun-surface-Dawn angle (known as the phase angle) of 0°. Combining images from that perspective with images taken at other phase angles reveals detailed properties of the material on the ground on scales much smaller than the spatial resolution of the camera, indeed approaching the wavelength of light.

The transfer to the new orbit, XMO4, was executed between Feb. 23, 2017, and April 13, 2017. A two-part trajectory correction maneuver (TCM) was planned for April 22 and 24 in order to ensure the phase would actually reach 0°. Dawn's third reaction wheel fault occurred between the two segments. Fortunately, the first part of the TCM was so good that XMO4 did indeed go through 0°, and the operations team was able to recover from the safe mode that occurred when the wheel failed in time to perform the observation, providing unique new data on the dwarf planet.

Throughout XMO3 and XMO4, Dawn continued its cosmic ray measurements. Dawn has no single-wheel mode, so after the third reaction wheel fault, attitude control was accomplished exclusively with hydrazine and with the IPS during thrusting. In XMO4, Dawn ranged from about 14,000 km to 53,000 km with a period of nearly two months. Nevertheless, hydrazine consumption was low enough that a second extended mission (XM2) was deemed feasible. To provide flexibility for XM2 while NASA assessed new options, Dawn used the IPS to maneuver to XMO5. XMO5 ranged in altitude from 5,300 km to 38,000 km with a period of one month.

In October 2017, NASA approved XM2. This final extended mission used the remaining hydrazine in an elliptical orbit with a periapsis altitude of only 35 km, compared with the LAMO/XMO1 altitude of 385 km. There was not enough hydrazine to transfer to nor operate in a 35-km altitude circular orbit. It took the operations team more than six months to develop methods and plans for operating in a highly elliptical orbit with a low periapsis. Once again, the primary objective was nuclear spectroscopy, although the opportunity for high resolution images, infrared and visible spectra, and gravity measurements made this a very appealing option.

IPS thrusting from April 16, 2018 to May 4, 2018 lowered the orbit most of the way. Dawn stopped then in XMO6 in order to perform new observations, principally in the southern hemisphere where it was summer and so lighting was optimal. (The Cerean year is 4.6 terrestrial years, and all of Dawn's prior observations had been when the Sun was in Ceres' northern hemisphere.) With an orbit ranging from 440 km to 4,700 km, Dawn acquired new data at altitudes between LAMO/XMO1 and HAMO/XMO2.

From May 31 to June 6, Dawn transferred to the final orbit of the mission, XMO7, with a periapsis of 35 km. The apoapsis of 4,000 km was chosen to provide an orbit period of 27.2 hours, exactly three times Ceres' rotation period. This resonance enables repeated nuclear spectroscopy measurements over the same longitude. Periapsis shifts south by nearly 2°/revolution, allowing a refined measurement of the subsurface ice content as a function of latitude. Once the orbit parameters are well measured, a pair of TCMs are scheduled for June 19 and 21 to improve this resonance condition.

Science data acquisition will continue in XMO7 until the hydrazine is exhausted, which will occur between August and October 2018. Without hydrazine, attitude control will not be possible, and the mission will conclude. A summary list of orbit maneuvers for extended missions XM1 and XM2 is provided in Table 4.

Table 4. Summary of IPS thrusting for Ceres science orbits. Colored rows indicate activities using IPS.

| Event | Time Period | Altitude Above Ceres (km) | Xenon Use (kg) |
|---|---|---|---|
| Start XM1 and XM01 Science | 7-1-16 to 9-1-16 | 385 x 385 | |
| Transfer to XM02 Orbit | 9-2-16 to 10-6-16 | | 3.8 |
| XM02 Science | 10-7-16 to 11-3-16 | 1,480 | |
| Transfer to XM03 | 11-4-16 to 12-5-16 | | 3.6 |
| XM03 Science | 12-6-16 to 2-22-17 | 7,530 x 38,550 | |
| Transfer to XM04 with Plane Change | 2-23-17 to 4-22-17 | | 2.1 |
| XM04 Science | 4-23-17 to 6-2-17 | 14,000 x 53,000 | |
| Transfer to XM05 Orbit | 6-3-17 to 6-23-17 | | 1.5 |
| XM05 Science, End XM1 | 6-24-17 to 10-17-15 | 5,300 x 38,000 | |
| Start XM2, XM05 Science | 10-18-17 to 4-15-18 | 5,300 x 38,000 | |
| Transfer to XM06 | 4-16-18 to 5-4-16 | | 3.8 |
| XM06 Science | 5-5-18 to 5-30-18 | 440 x 4,700 | |
| XM07 Transfer | 5-31-18 to 6-6-18 | | .8 |
| XM07 Science | 6-7-18 to 9-30-18* | 35 x 4,000 | |
| XM1 and XM2 Xenon Used (kg) | | | 15.7 |
| XM1 and XM2 Beam Extraction Time (h) | 2,942 | | |

*Notional date for end of mission when hydrazine is exhausted

## IPS System Power and PPU Performance

Spacecraft heliocentric range for the complete mission is plotted in Figure 4. The blue line color in the figure depicts periods during the mission when IPS was used for thrusting. As expected for a low thrust mission, the IPS is on and thrusting for the majority of mission time for deterministic thrusting to achieve rendezvous, and a minority of the time at the target body to accomplish orbit transfers. After reaching a maximum solar distance of 2.98 AU in early January 2016 the Dawn spacecraft moved inbound to the sun, increasing the power available to the IPS during its extended missions. During the extended missions the minimum distance to the sun of 2.55 AU was reached in April 2018.

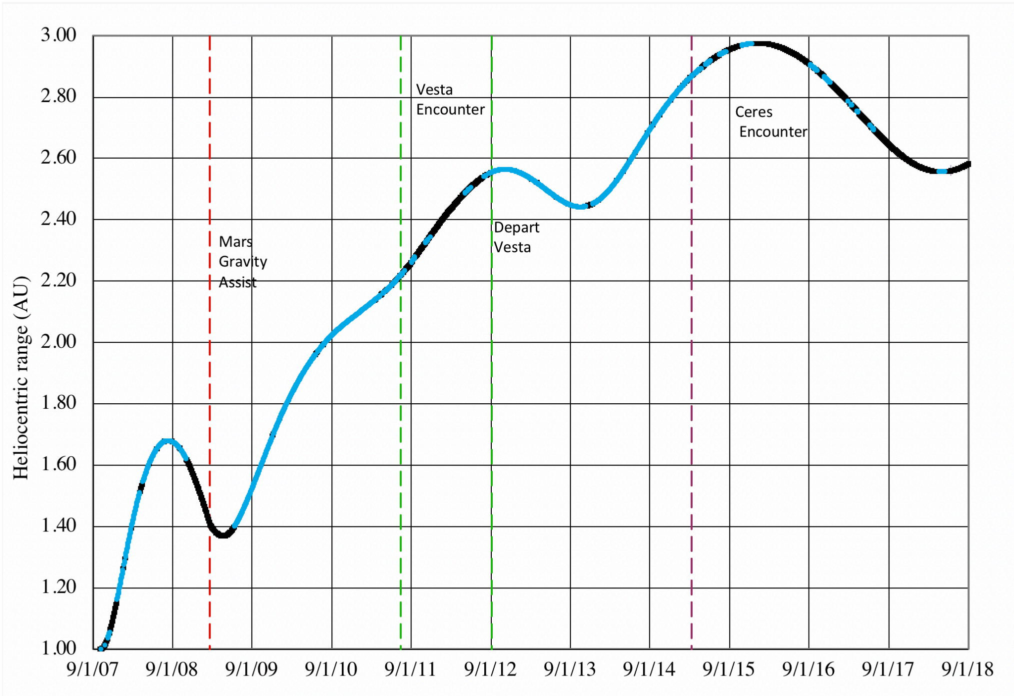


Figure 4. Spacecraft heliocentric range from launch through end of mission. Blue line color denotes IPS thrusting.

During the extended missions only PPU-2 was used. Data for high voltage PPU power for the complete mission are plotted in Figure 5. Data points in Figure 5 are the values averaged at a fixed power level. The data include telemetry for unregulated high voltage and current from the solar array to the PPUs and do not include PPU housekeeping power of approximately 20 W. The full Dawn throttle table includes 112 separate operating points called mission levels, with about 20 W separating each different power level. Input power to PPU-2 during deterministic thrusting for the extended missions varied from 0.7-1.1 kW. For the full mission, input power to the PPUs varied from a low of 0.45 kW at “mission level 1” during a solar array test to a high of 2.5 kW, a power throttling ratio of about 5:1.

Both PPUs have operated nominally throughout the mission to date, and PPU performance throughout the mission has been excellent. PPU efficiencies at 0.5-2.5 kW are similar to the efficiencies measured preflight and were consistently in excess of 93% at full power, not including PPU low voltage power. PPU efficiencies at lower power are greater than measured pre-flight, likely due to telemetry calibration inaccuracies at low power. Beam currents controlled by the beam supplies in both PPUs were typically within 0.995 of the set point values based on telemetry, and neutralizer current and accelerator grid voltage were at the set point.

In Figure 6 data (averaged over individual thrust arcs) from temperature sensors inside the PPU indicate that PPU temperatures changed a few degrees C during cruise at full power, and decreased upon start of power throttling. The PPU baseplate temperature sensors are mounted to the part of the PPU chassis in contact with the spacecraft thermal control surface. After the start of cruise to Ceres PPU control surface temperature was set to a low value to conserve heater power, but the PPUs have been kept well within their flight allowable temperature limits. Baseplate temperatures from telemetry have ranged between 27 degrees C with the thrusters operating at full power to 12 degrees C with PPU-2 operating at 0.7 kW. The fact that the PPU baseplate temperatures are near room temperatures even for full power operation is a reflection of the well-designed thermal heat rejection system on the Dawn spacecraft.

Temperatures of the harness connectors mating the thrusters to the PPUs are shown in Figure 7. The data indicate that at full power operation connector temperatures ranged between 10 to 45 degrees C, and at lower power the harness connector temperatures were as low as -17 degrees C, well within operational temperature limits of -55 to +90 degrees C. The temperature excursions experienced by the FT3 harness connector in 2011 and the FT2 harness connector for operations at Ceres are due primarily to changing solar exposure to the spacecraft, a consequence of orbit operations.

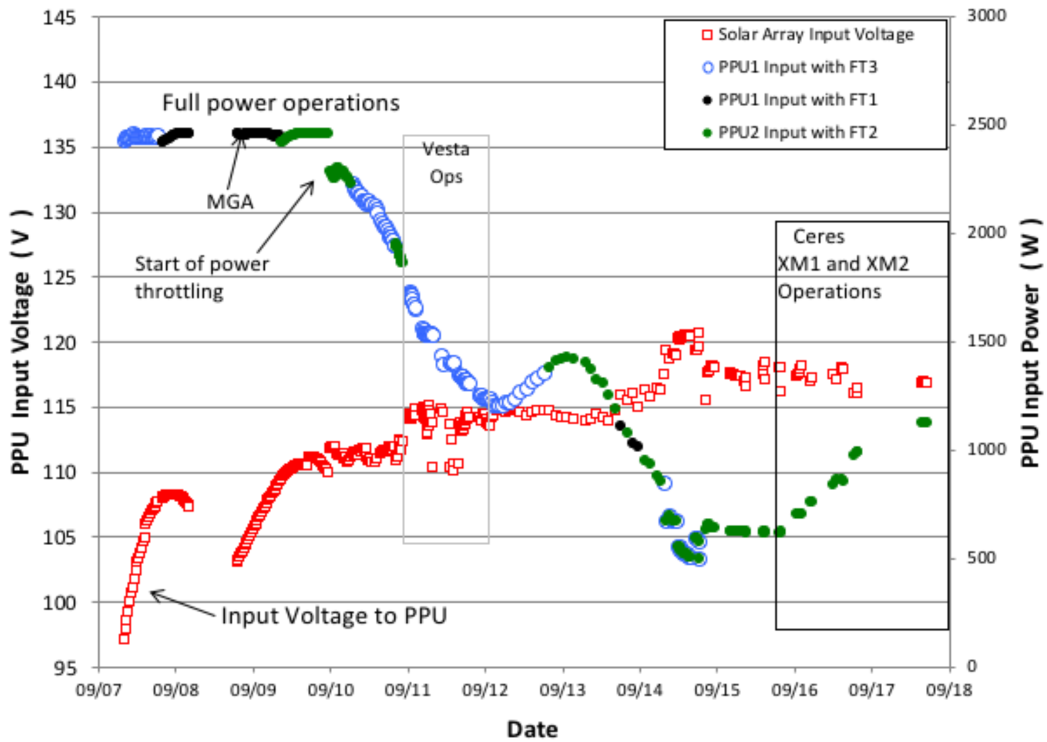


Figure 5. Solar array input voltage and PPU operating power from start of cruise to Vesta through end of mission.

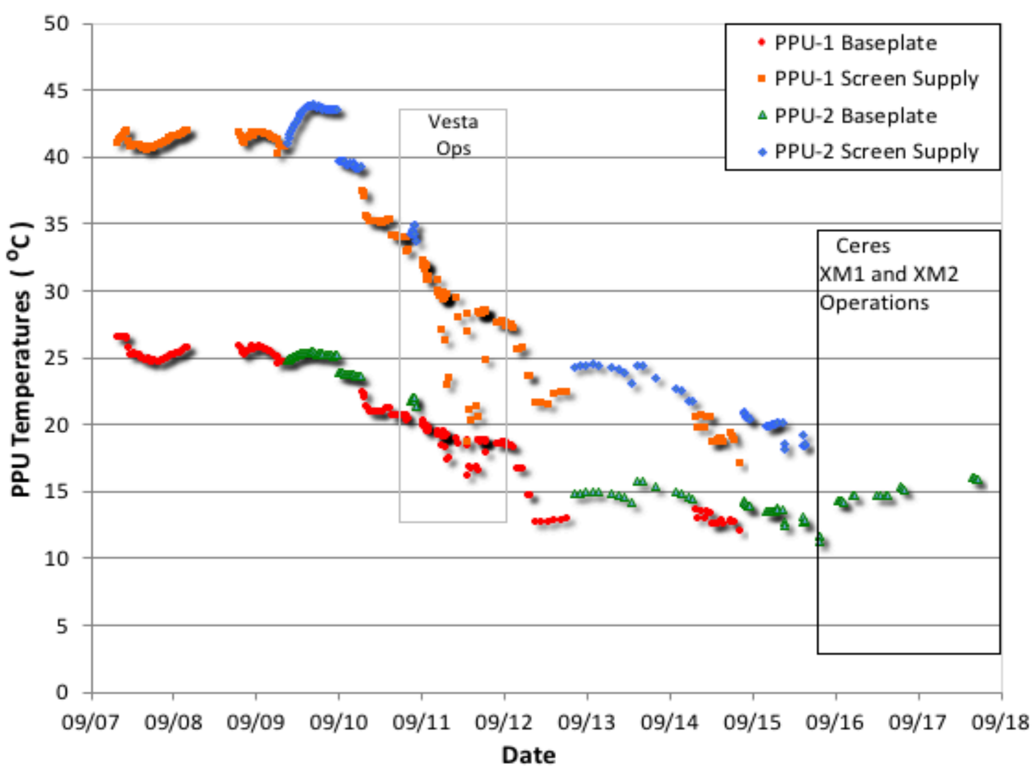


Figure 6. PPU-1 and PPU-2 temperatures from start of cruise to Vesta through through end of mission.

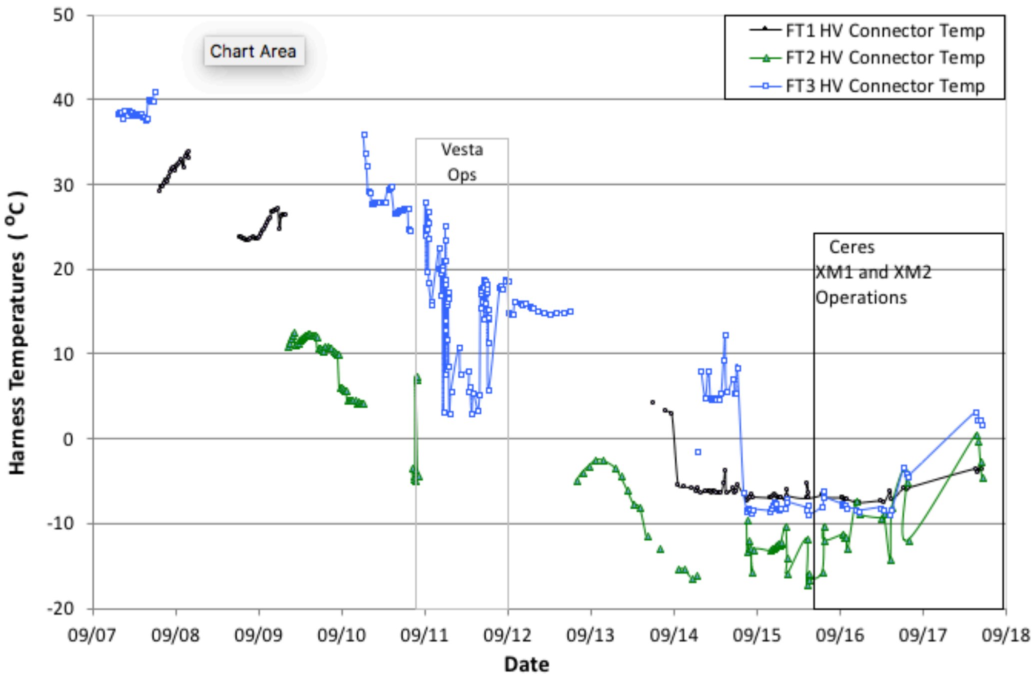


Figure 7. Harness connector temperatures from start of cruise to Vesta through through end of mission.

**XFS Performance**

The xenon flow system has operated almost perfectly throughout cruise, with the exception of higher than expected solenoid valve cycling rates (as described in [8]) that did not pose a threat to mission reliability, and a very low-rate leak through a latch valve in the cathode flow line. Plenum tank pressures are controlled by actuation of the solenoid valve pairs between the main xenon tank and plenum tanks. Orbit transfers in XM2 were performed at fixed main and cathode flow rates to improve maneuver execution errors. To date the primary solenoid valve pair used to regulate main plenum pressure has been cycled approximately 1.4 million times in cruise, and the primary solenoid valve pair for cathode plenum tank pressure regulation has cycled approximately 0.8 million times (Figure 8). The solenoid valves on the Dawn XFS have a flight allocation of 1.25 million cycles, so the main pair have exceeded their operational life. In July 2017 flow operations were switched to the redundant solenoid valve (SV) pair to compare operational characteristics to those of the primary SV pair. To date the redundant main SV pair has accumulated approximately 100,000 cycles and the redundant cathode pair about 90,000 cycles. Solenoid valve cycle rates at fixed flow rates increase as the density of the xenon in the main tank decreases and as the pressure differences between the inter-solenoid valve space and plenum tanks decrease. At the conclusion of thrusting on June 6, 2018 the main SV pair cycled at a rate of 163/hour, well within the capabilities of the XFS to supply xenon at the required flow rate of 9.73 sccm. The controlling temperature for the xenon control assembly plate was reduced early in cruise to reduce the solenoid valve cycle rate [13]. There are no indications of solenoid valve leakage based on observations of SV cycling characteristics. Steady-state pressure telemetry of the plenum tanks made during periods of non-IPS use indicated the possibility of a very low-rate leak of approximately 2 g/year beginning in September 2016. Since the leak rate was so low no changes were made in flow system operations. Each plenum tank has three plenum pressure transducers. Telemetry of the differences between the three transducers for each plenum tank, as measured by DCIU-1 and DCIU-2 and shown in Figures 9a-9d, indicate little change in output between the different pressure transducers.

Total xenon use throughout the mission was estimated using integrated flow rates over time. This FCD model, which uses plenum tank pressures and FCD temperatures for calculating flow rates, is considered to be the most accurate way of estimating xenon use for individual xenon-consuming events. Over Dawn's almost 11 years of operations, however, errors/uncertainties from FCD calibrations and flight telemetry data have accumulated such that although the errors are a low percentage of the propellant used, they are a high percentage of the estimated xenon remaining.

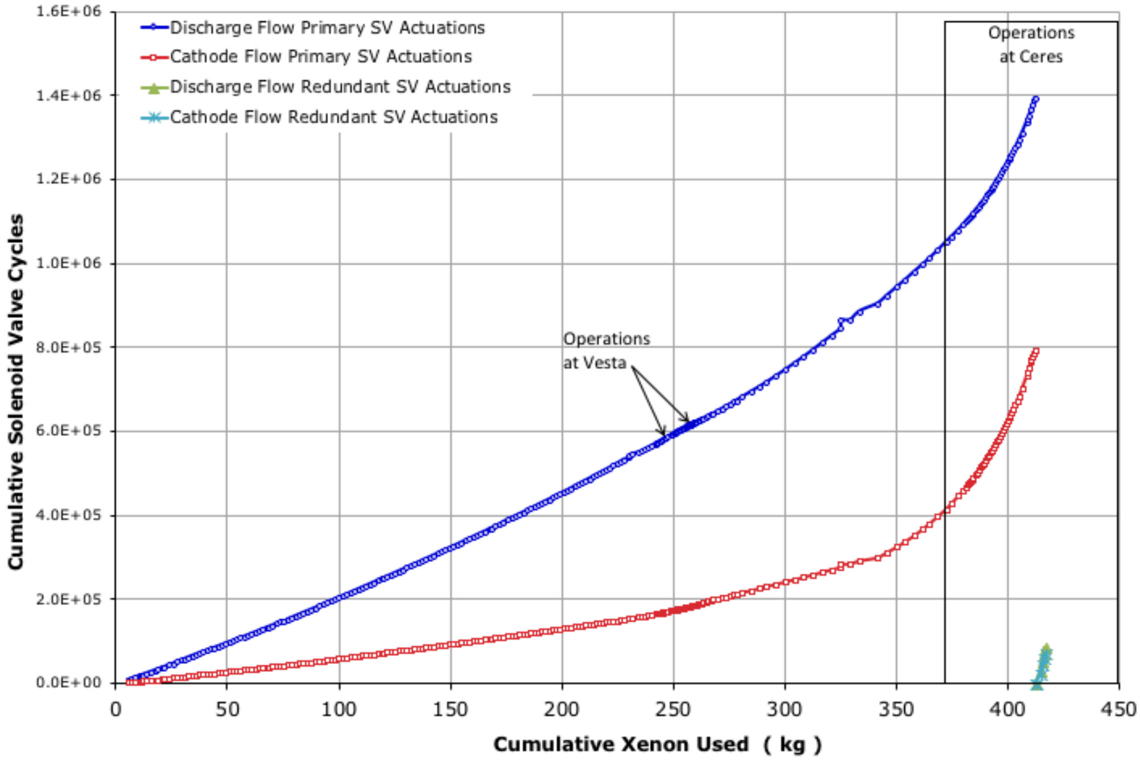


Figure 8. Cumulative number of discharge and cathode SV cycles vs. xenon consumed from launch through through end of mission.

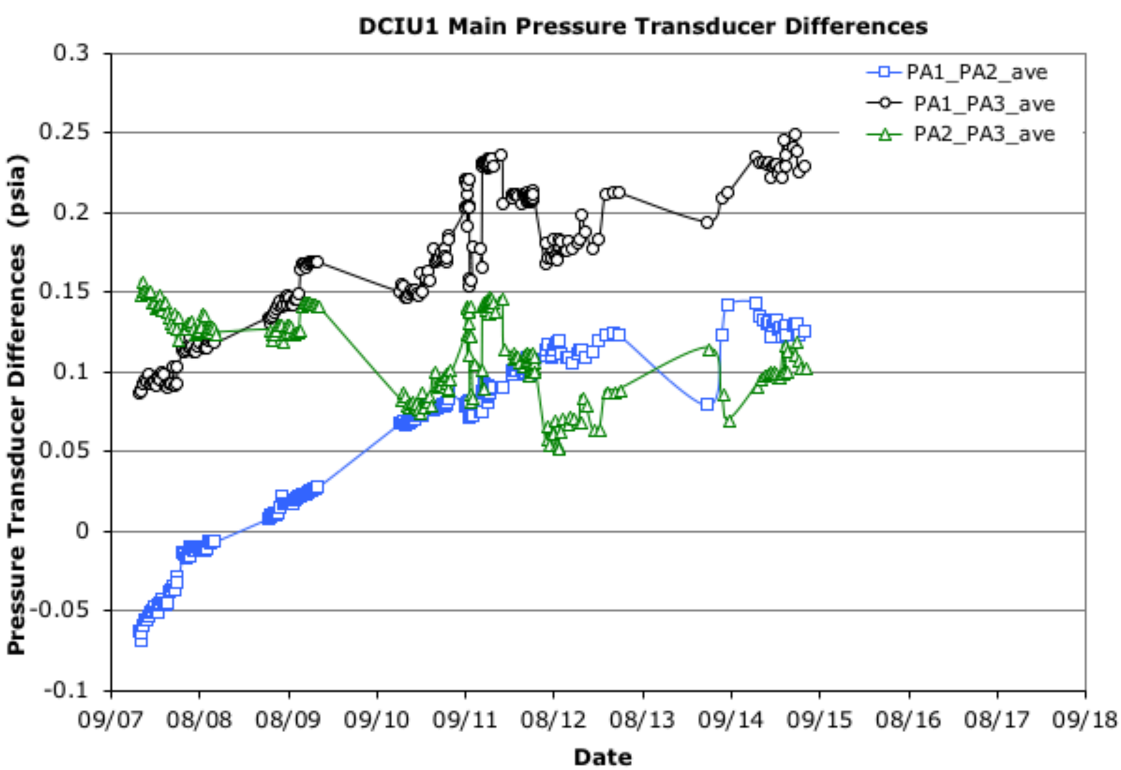


Figure 9a. Discharge plenum tank pressure transducer differences over time as measured by DCIU-1.

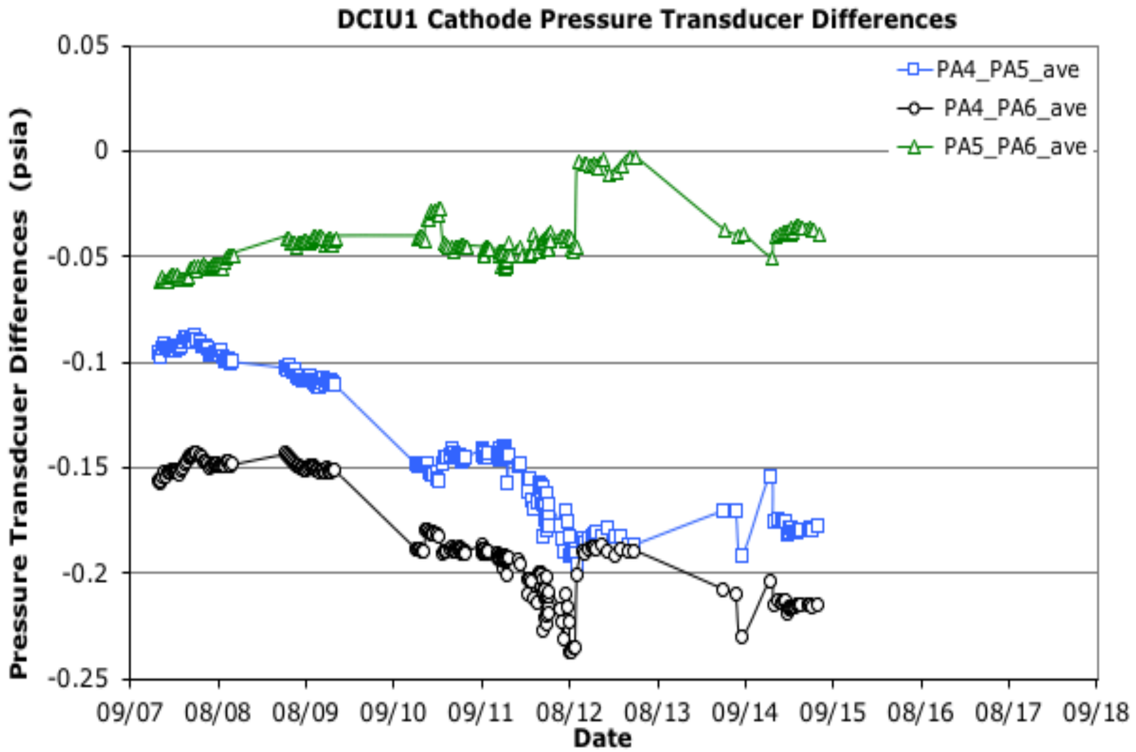


Figure 9b. Cathode plenum tank pressure transducer differences over time as measured by DCIU-1.

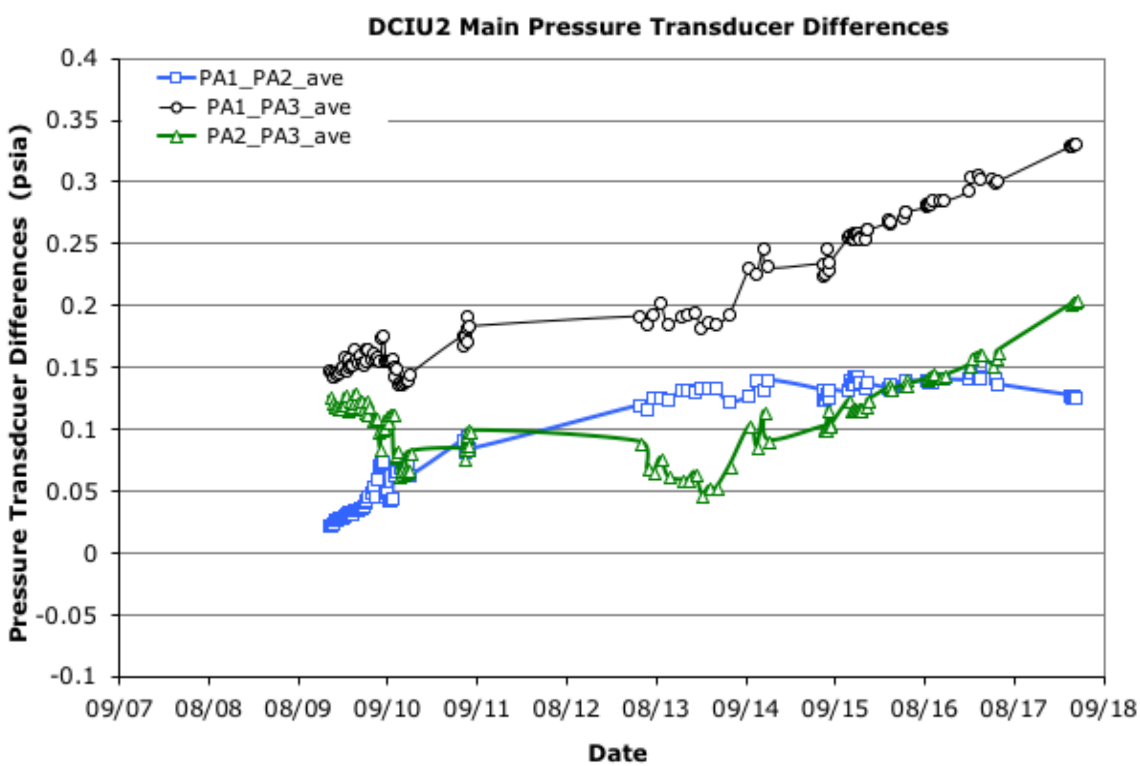


Figure 9c. Discharge plenum tank pressure transducer differences over time as measured by DCIU-2.

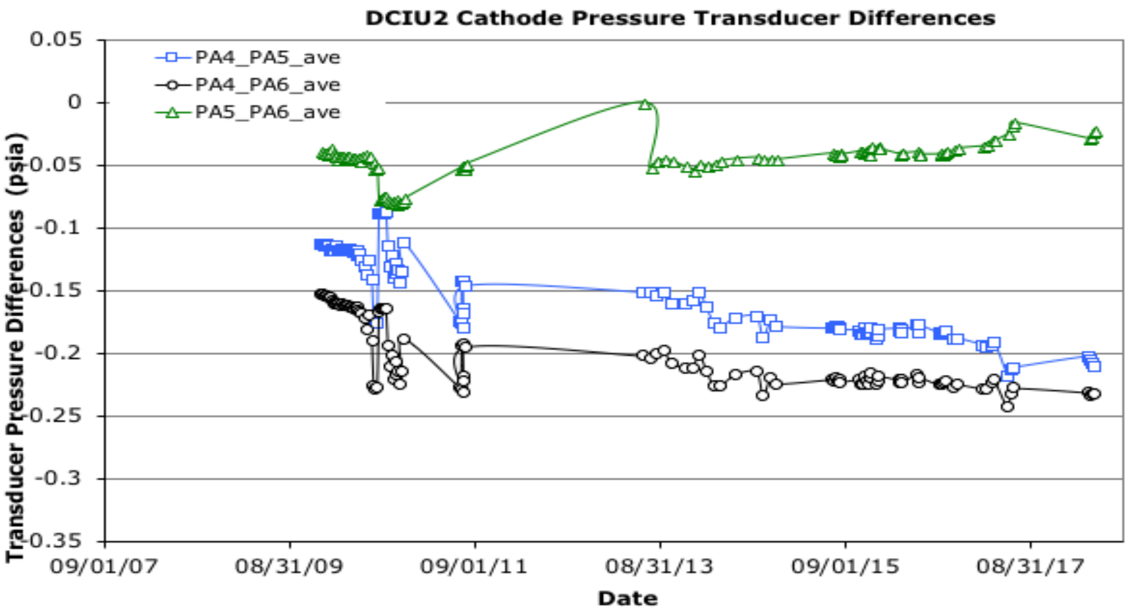


Figure 9d. Cathode plenum tank pressure transducer differences over time as measured by DCIU-2.

Xenon consumption and remaining xenon on-board were re-evaluated after the last orbit maintenance maneuver in April 2016 to support concept studies of options for extending Dawn's mission beyond June 2016. Two different approaches were evaluated to develop estimates for xenon remaining on the Dawn spacecraft: the flow control device model (FCD) that has been used to account for xenon consumed since launch, and pressure-volume-temperature (PVT) models. The PVT-XeTank model uses xenon storage tank pressure and temperature telemetry to estimate xenon remaining. For the FCD and PVT methods, xenon remaining and uncertainties were evaluated based on standard practices used by JPL's Propulsion Section for determining quantity and uncertainties for hydrazine and helium tanks. The models called PVT-SV Main and PVT-SV Cath used plenum tank pressure transducer telemetry and cycling characteristics of the SVs to estimate the pressure in the xenon storage tank supplying xenon to the SVs. Once the storage pressure was estimated, the storage tank temperatures were then used to estimate xenon in the storage tank with the standard PVT approach. Analysis indicates the PVT-SV Main and PVT-SV Cath models have lower uncertainty than the other methods for estimating xenon remaining. For all PVT models, uncertainty in the estimates is dominated by worst case assumptions on pressure transducer drift.

Results are summarized in Table 5. Analysis from the FCD model indicates there are 8.6 ±4.8 kg of xenon remaining at 2-sigma uncertainty. The current best estimates (CBE) for the three PVT models agree to within ±0.2 kg. Solenoid valve cycling rates depend upon the density of the xenon in the xenon storage tank. Solenoid valve cycle rate data from the last time Dawn IPS was operated with xenon flow are consistent with a xenon storage tank pressure measurement and temperature measurements made during Dawn's final maneuver, leading to additional confidence in the PVT model.

**Table 5. Xenon Remaining on the Dawn Spacecraft June 2018**

| Evaluation Method | Minimum Xenon Remaining | Nominal Xenon Remaining | Maximum Xenon Remaining | Uncertainty |
|---|---|---|---|---|
| | (kg) | (kg) | (kg) | (kg) |
| FCD | 3.8* | 8.6 | 13.4* | 4.8* |
| PVT-XeTank | 12.0 | 14.2 | 16.4 | 2.2 |
| PVT-SV Main | 13.0 | 14.0 | 15.0 | 1.0 |
| PVT-SV Cath | 12.9 | 13.8 | 14.7 | 0.9 |

*FCD model minimum, maximum and uncertainty values include uncertainty in the estimate of xenon loaded into the xenon storage tank pre-launch (±0.35 kg)

**TGA Performance**

The TGAs operated very well in orbit at Ceres. Each TGA consisting of two each motor/tripod assemblies (side A and side B) per FT was used to move the ion thruster vector to control the two axes normal to the thrust direction. This mode is known as thrust vector control (TVC). RWAs or RCS hydrazine thrusters are used to control the axis around the thrust vector. Cumulative TGA actuator motor revolutions for the A-side motors for each FT are shown in Figure 10. The B-side motors have almost the same number of revolutions. The data indicate that through June 2018 the TGA motors for FT2 accumulated the equivalent of over 3.45 million motor revolutions and approximately 27.6 million actuator steps. The motors were qualified to 30 million revolutions. The spacecraft was operated in TVC mode during normal thrusting, including during desaturations of the RWAs, which were typically sequenced approximately every 12 hours. TGA duty cycle varied between 0.05% in cruise to up to 9% for orbit operations. In normal operation the TGAs "dithered", or rotated, a small amount around a target center. The duty cycle and number of TGA actuations per kg of xenon used were greater with RWA control, which explains the high TGA usage on FT2 under hybrid RWA control (Figure 10). In Figure 10, the actuation rate for FT2 and FT3 decreased when the spacecraft switched to hydrazine thrusters for attitude control starting in June 2010. In May 2011 and again in December 2014 the spacecraft switched to the wheels for attitude control as part of operations for Vesta approach and Ceres approach and the TGA duty cycle increased substantially. TGA duty cycle rates under RWA control may increase because under RWA control the spacecraft issues more correcting commands to slew the TGAs than is done under jet control. Approximately every two months for TGAs in use (and six months for unused TGAs) lubricant in the actuators was redistributed by vectoring the thrusters from their null locations to the hard stops and then back to their null locations. The actuators on both FT1 and FT3 appeared to slip when first commanded, but this never resulted in an inability to point the thrust vector as needed. FT2's actuators have shown no indication of slipping, and FT2 was used for final Ceres orbit operations.

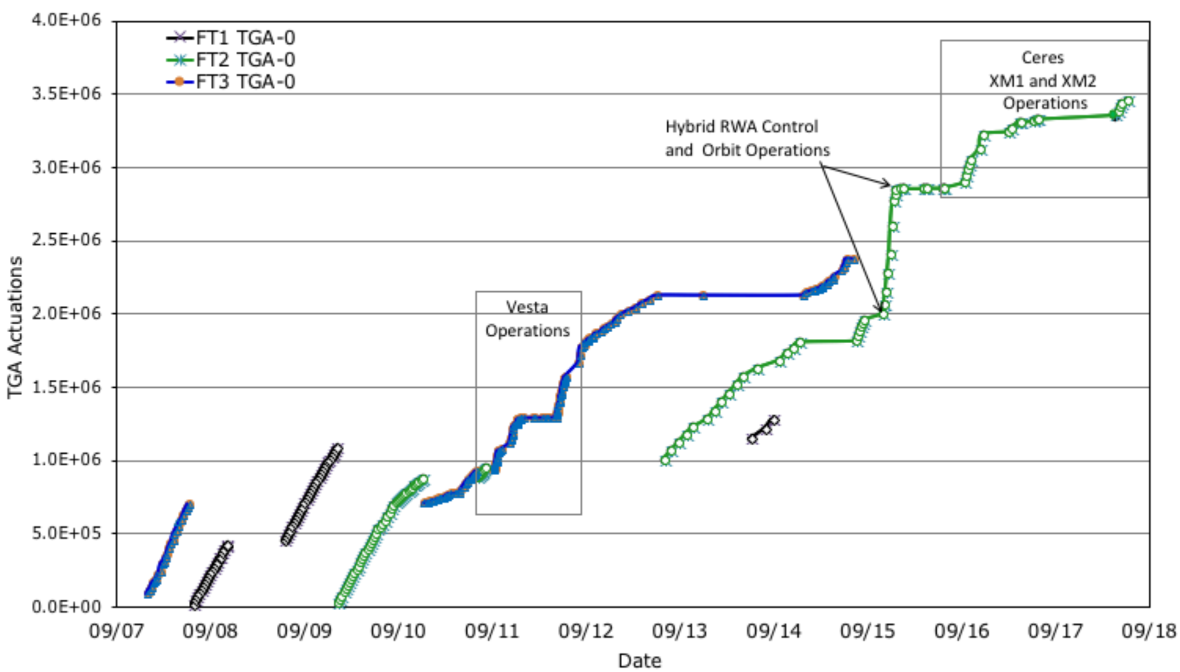


Figure 10. Cumulative number of TGA side A cycles vs. date, from launch through end of mission.

**Thruster Performance**

Thruster performance data from the ICO were presented in [8] and detailed thruster performance from the start of cruise to Vesta through the final Ceres maneuver are presented here. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness, which is estimated to be approximately 15 W for the discharge and 18W for the thruster at full power. During operations at Vesta, and for some of cruise to Ceres and Ceres orbit operations the thrusters were operated at full power discharge cathode and neutralizer flow rates, and in some cases high main flow rates, to minimize maneuver execution errors as described in [17].

**IPS Operating Time and Thruster Xenon Consumption**

Table 6 summarizes operating time for each thruster/PPU and xenon throughput from launch through June 2018. The xenon throughput in Table 6 uses values estimated from the FCD model as described previously. Dawn completed all deterministic thrusting and orbit maneuvers with a cumulative total of approximately 51,382 hours of thruster beam-on time. Operating time for the primary mission was 48,458 hours, close to the estimate at launch of 48,000 hours. FT2 has accumulated the most number of operating hours and xenon throughput, and Dawn has operated all three thrusters to more evenly distribute the total xenon consumed by each thruster. For the mission, FT2 was operated at 90% of its throughput allocation, 73% of the xenon throughput accumulated by the thruster in the ELT[14], and over 2.3 times the xenon throughput accumulated by the DS1 ion thruster. For transfers from one science orbit to another around Vesta and Ceres, in which the operational schedule requires a rapid design and implementation of the thrust profile, FT3 is preferred because FT3's thruster axis is aligned with the principal axis of the spacecraft. Nevertheless, transfers with the other thrusters are feasible, any of the three Dawn thrusters can and were used for any maneuver, and in fact FT2 was used for most of the maneuvers performed at Ceres. In Table 6 PPU operating time is defined as when any of the individual supplies within the PPU, including cathode heater supplies, are on and outputting power.

Table 6. Operating time and xenon throughput for Dawn ion thrusters from launch through June 2018.

| IPS Element | Neutralizer On-Time ( h) | Beam On-Time ( h ) | Xenon Throughput* ( kg ) | Thruster Starts |
|---|---|---|---|---|
| FT1 | 9524 | 9468 | 95.1 | 122 |
| FT2 | 22,843 | 22,772 | 171.4 | 209 |
| FT3 | 19,311 | 19,141 | 150.1 | 367 |
| Thruster Totals | 51,678 | 51,382 | 416.6 | 699 |
| | | | | |
| PPU-1 (h) | | 28,884 | | |
| PPU-2 (h) | | 22,864 | | |
| PPU Totals (h) | | 51,748 | | |

*Throughput based on FCD model

**IPS Operating Time and Xenon Consumption**

Figures 11-12 include thruster input power and beam power vs. xenon throughput and beam extraction time over the complete mission. Values in the figure are averaged values over specific thrusting events. Thruster input power includes the neutralizer, discharge, beam, and accel power. Dawn experienced maximum thruster power using FT1, operating at full power of 2.3 kW. After operation of each thruster at full power for a period exceeding 3,800-6,800 hours power consumption for each thruster had increased by

16-22 W over power use measured during the ICO [8]. Small increases in total thruster power are expected due to wear in the accelerator grid hole walls. After completing operations at full power each thruster experienced a decrease in thrust of up to 2% compared to values expected from thruster electrical parameters. Thruster power was throttled beginning in 2010 as the spacecraft's distance from the sun increased, decreasing output from the solar array and reducing power available to the IPS. Figures 11-12 include operations with off-nominal cathode and main flow rates, which reduced thruster operating power by as much as 60 W or more. In addition, thrust increased by 1-2% or more compared to values expected from thruster electrical parameters, depending upon the throttle level and the amount of off-nominal (excess) flow rate to the engines. Operations at fixed flow rates eliminated flow rate excursions but made predicting thruster operating power and thrust, characteristics used in maneuver design a challenge. Minimum operating power of approximately 463 W for deterministic thrusting occurred during operations on FT3. Beam power ranged from 1.93 kW at the start of the mission through 0.37 kW at Ceres apogee, spanning a total beam power range ratio of 5.2. Thrust ranged from 91.3 mN for full-power operation through 22 mN with FT3 during Ceres orbital operations.

**Discharge Voltage**

Discharge telemetry for the three Dawn ion engines through June 2018 are shown in Figures 13a and 13b. During the last part of cruise to Ceres and orbital operations there, high cathode and sometimes high discharge flow rates were used while thrusting with FT2 and FT3. Voltage measurements are determined from telemetry at the PPU and the data have not been corrected for the power drop across the harness. Discharge voltage changes for all three thrusters from approximately 45-85 kg of xenon throughput are explained by changes to lower power levels. Full power cathode flow rates were used for orbit maneuvers at both Vesta and Ceres to address the thrust stability issues that are described in [17]. This change resulted in extremely reliable and consistent maneuvers, and suppressed the discharge voltage (Figure 13a). Operation with nominal cathode flow rates was resumed beginning October 1, 2012, until April 2014 when all three engines were switched to operations at rich cathode flow rates.

For all three engines at full power, discharge voltage and power initially increased then stabilized. This is likely related to accelerator grid hole wear characteristics, which result in higher grid transparency to ions. Abrupt changes in discharge voltage exceeding approximately one volt are related to changes to the cathode flow rates from nominal values to full power values or to power level changes.

At approximately 110 kg of xenon throughput for FT2 and FT3 the discharge voltage for both thrusters began to increase at a rate of approximately 0.1 V per kg of xenon throughput, with this rate increasing over time and xenon consumed. The corresponding discharge current decreased. Both engines were operating at nominal cathode flow rates when the discharge voltage characteristics began changing. The most significant differences in operations on FT2 vs. FT3 through 0-110 kg of xenon throughput were FT2 has more operating time at greater power levels, fewer starts and substantially less operating time at high cathode flow rates. It is not known if the discharge voltage characteristics are indicative of wear in this thruster design, since the keeper material was changed from molybdenum to tantalum. The discharge cathode flow rate was changed to full-power cathode flow rate for FT3 at 135 kg xenon throughput and 125 kg for FT2. This change in cathode flow rate changed the discharge voltage changed by over 3 volts and the rate of increase in discharge voltage slowed. Dawn maintained substantial margin to the discharge voltage supply capability throughout all phases of the mission.

**Thruster Starts**

From launch through operations at Ceres LAMO there have been a total of 679 thruster starts in flight, with 122 starts using FT1, 209 starts using FT2, and 367 starts using FT3. Approximately 322 of these engine starts were on the discharge only for one hour (called "diode mode) to prepare the engine thermally for beam extraction, or were for various time periods for in-flight thruster tests. The cathode heater preheat duration for all starts was six minutes. Data taken at one second intervals indicate that in every start attempt in flight after the ICO, the discharge and neutralizer cathodes ignited within one second of the command for application of the igniter voltage pulses. Discharge cathode and neutralizer cathode heater power appear unchanged over time, possibly indicating low levels of keeper electrode erosion over time. Beginning in December 2014 all thrusters were started without using a thruster discharge pre-heat cycle. The highest power level for a thruster start without a thruster discharge pre-heat was at approximately 800 W on FT3.

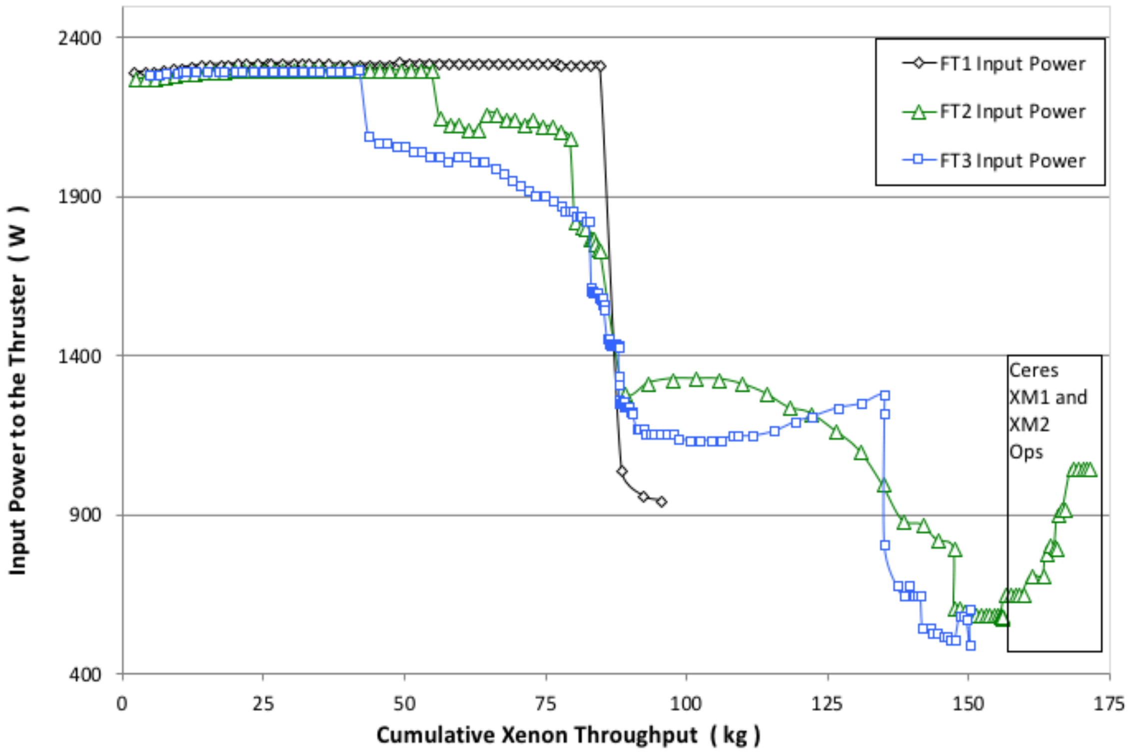


Figure 11a. Dawn thruster input power vs. thruster throughput from start of cruise to Vesta through June 2018.

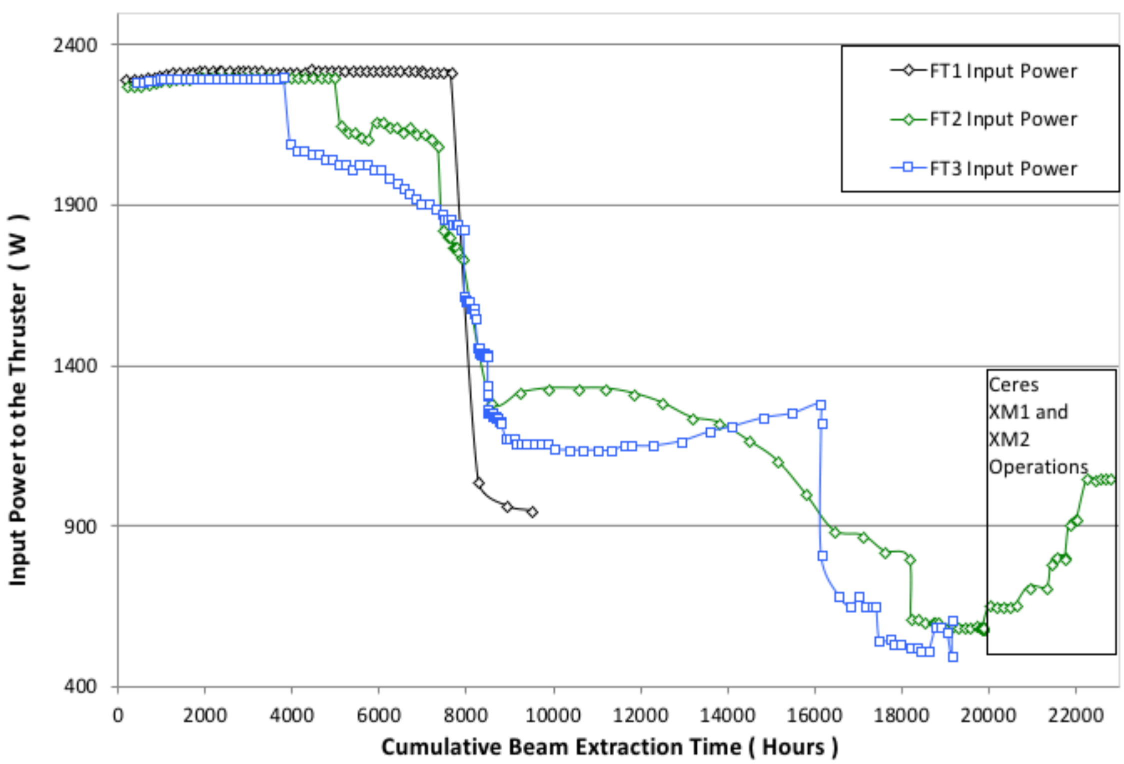


Figure 11b. Dawn thruster input power vs. thruster operating time from start of cruise to Vesta through June 2018.

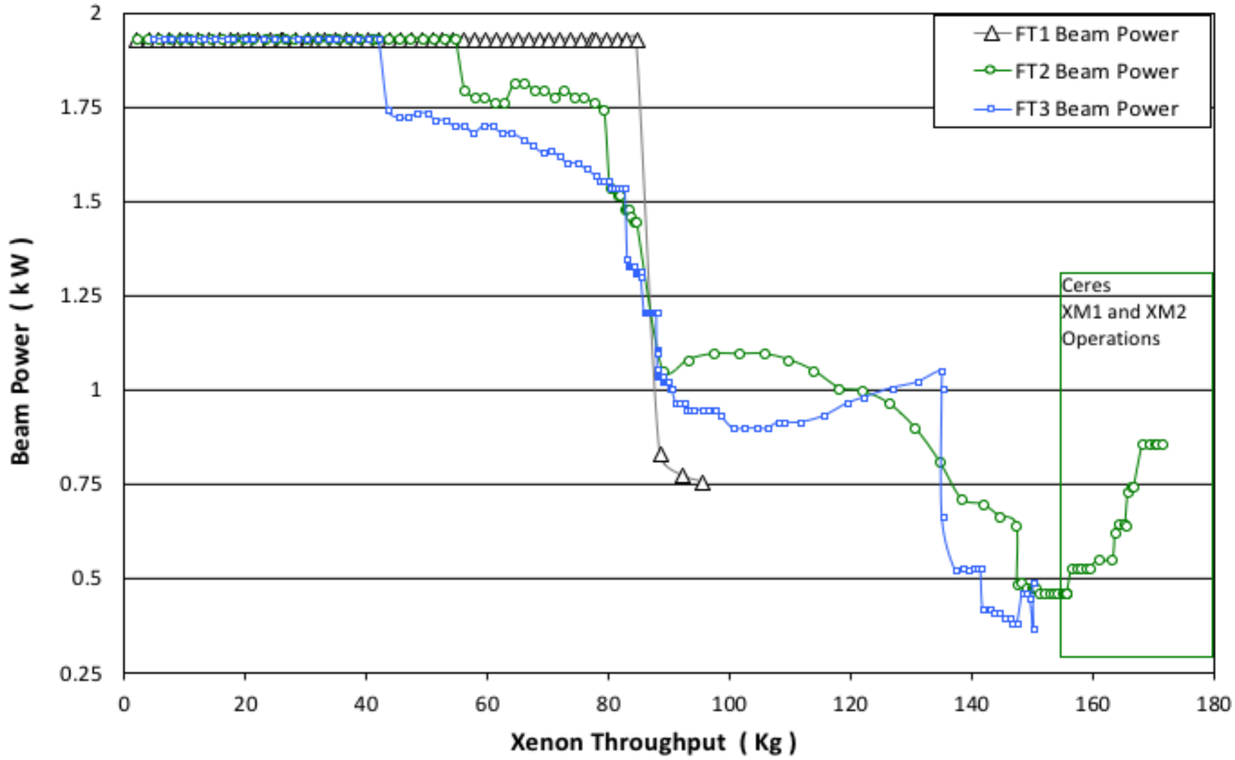


Figure 12a. Dawn thruster beam power vs. FT throughput from start of cruise to Vesta through June 2018.

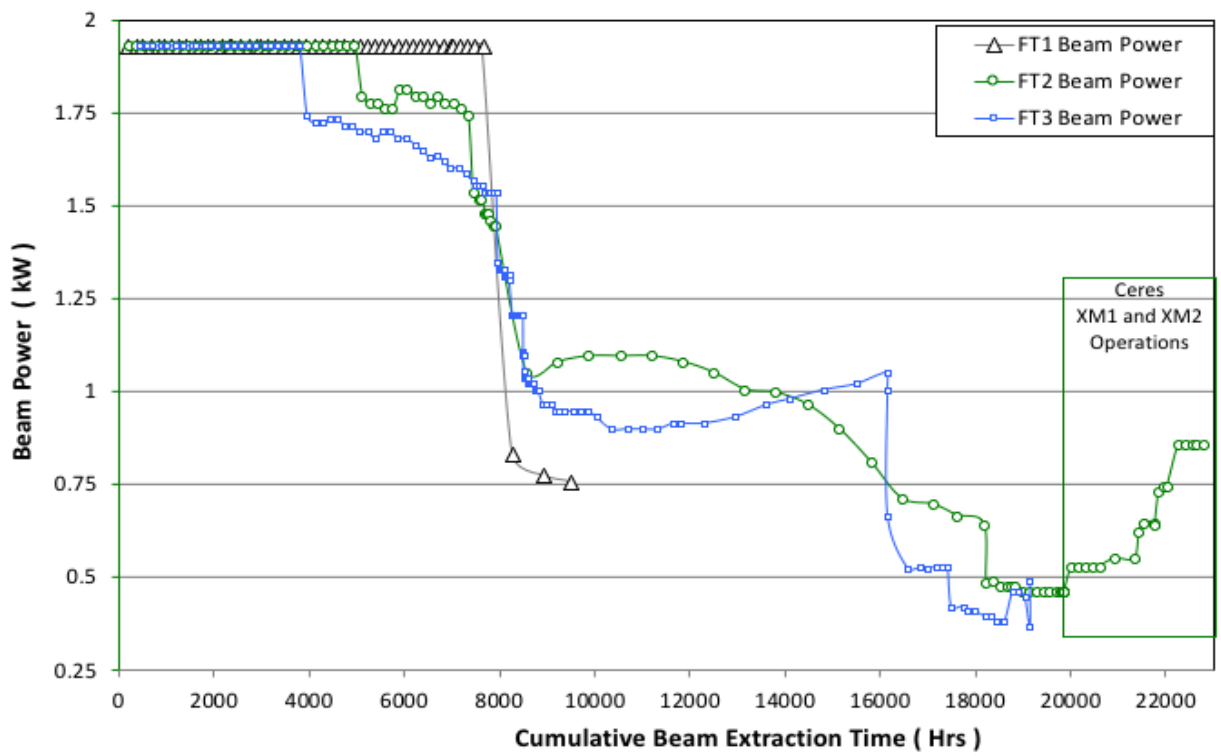


Figure 12b. Dawn thruster beam power vs. beam extraction time from start of cruise to Vesta through June 2018.

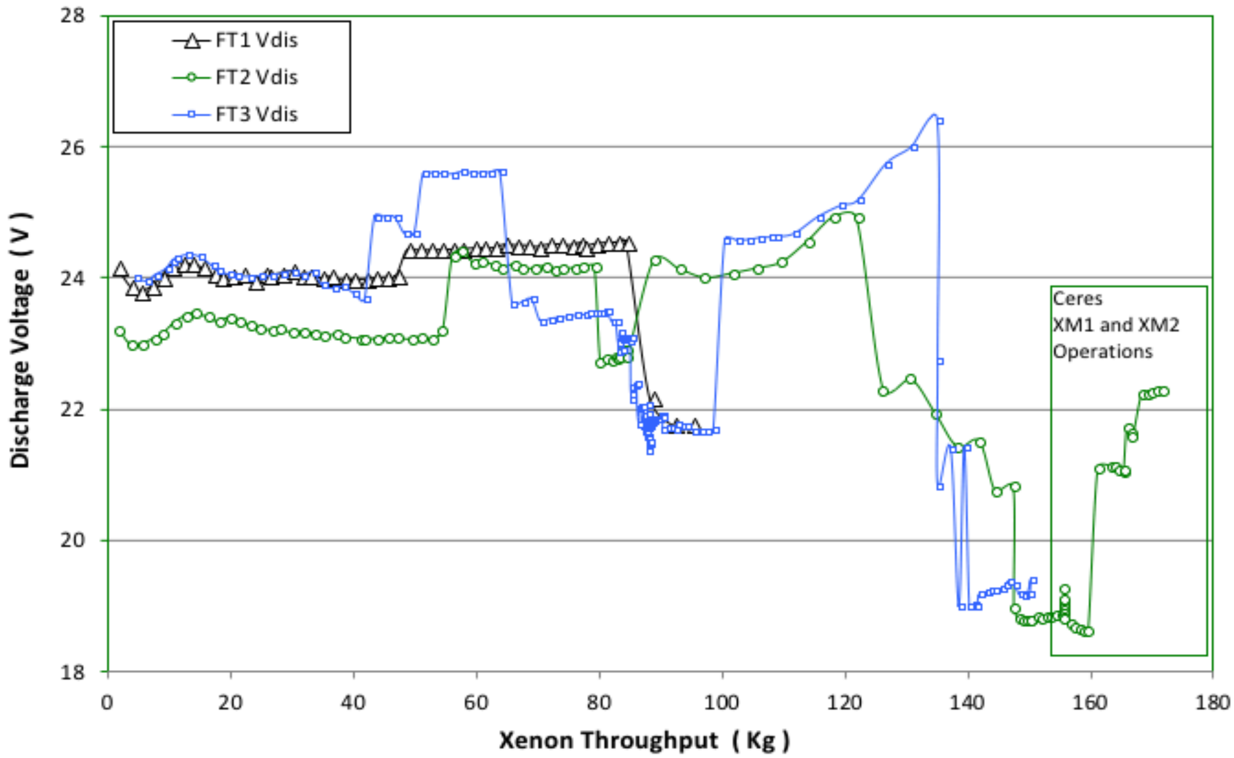


Figure 13a. Dawn thruster discharge voltage vs. xenon throughput from start of cruise to Vesta through June 2018.

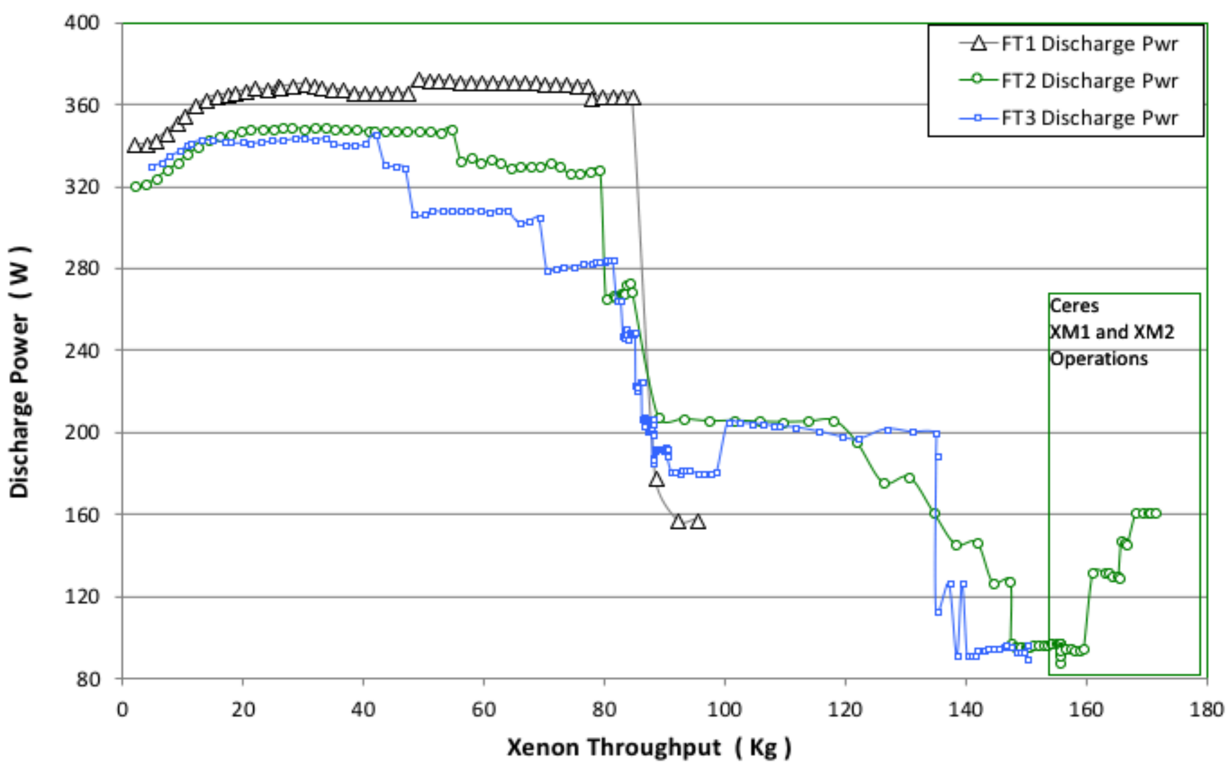


Figure 13b. Dawn thruster discharge power vs. xenon throughput from start of cruise to Vesta through June 2018.

**Neutralizer Operation**

Dawn thruster neutralizer keeper voltage data for operation from start of cruise to Vesta through June 2018 are shown in Figure 14. From the start of cruise to approximately 80 kg of xenon throughput neutralizer keeper voltages decreased in a similar way for all three Dawn thrusters. Dawn thruster neutralizer voltage changes may be related to improved cathode conditioning over time in the clean environment of space. Smaller changes to the neutralizer voltage appear to be due to thruster power changes, while larger changes are related to operating the engines at moderate to low power with rich cathode flow rates, which suppresses the neutralizer voltage (Figure 14).

The neutralizer cathode must be operated at the proper flow rate and neutralizer keeper emission current to result in the nominal operating mode referred to as "spot" mode. A potentially damaging neutralizer operating condition called "plume mode" is characterized by greater than nominal neutralizer keeper voltage and greater alternating current (AC) noise in the direct-current (DC) neutralizer keeper plasma. This mode can lead to life-limiting erosion in the neutralizer. A plume mode detection circuit in each Dawn PPU converts variations in the AC component of the neutralizer keeper voltage to a DC voltage. The plume mode circuit voltage telemetry is monitored in flight to evaluate the health of the neutralizer. Dawn thruster plume mode circuit output data for each engine averaged over individual thrust segments are shown in Figure 15. In normal operation the plume mode circuit voltage increases after cathode ignition, when the neutralizer cathode is known to operate in plume mode. Plume mode circuit output then decreases to the lower, steady-state voltage during normal neutralizer operation that are shown in Figure 15, with the plume voltage decreasing at lower power levels and rich cathode flow rates. The largest change in plume mode circuit output for steady-state operations occurred for FT2, where both a moderate reduction in power and change to rich cathode flow rates resulted in a decrease in plume mode output of 0.4 V, from 1.5 V to 1.1 V (Figure 15). During all of Dawn IPS operations since launch there have been no indications of neutralizer cathode operation in plume mode after the initial start-up transients. Dawn's thrusters accumulated substantial operating time at low power, but plume mode circuit output data do not indicate any issues regarding plume mode as observed on the DS1 mission [2].

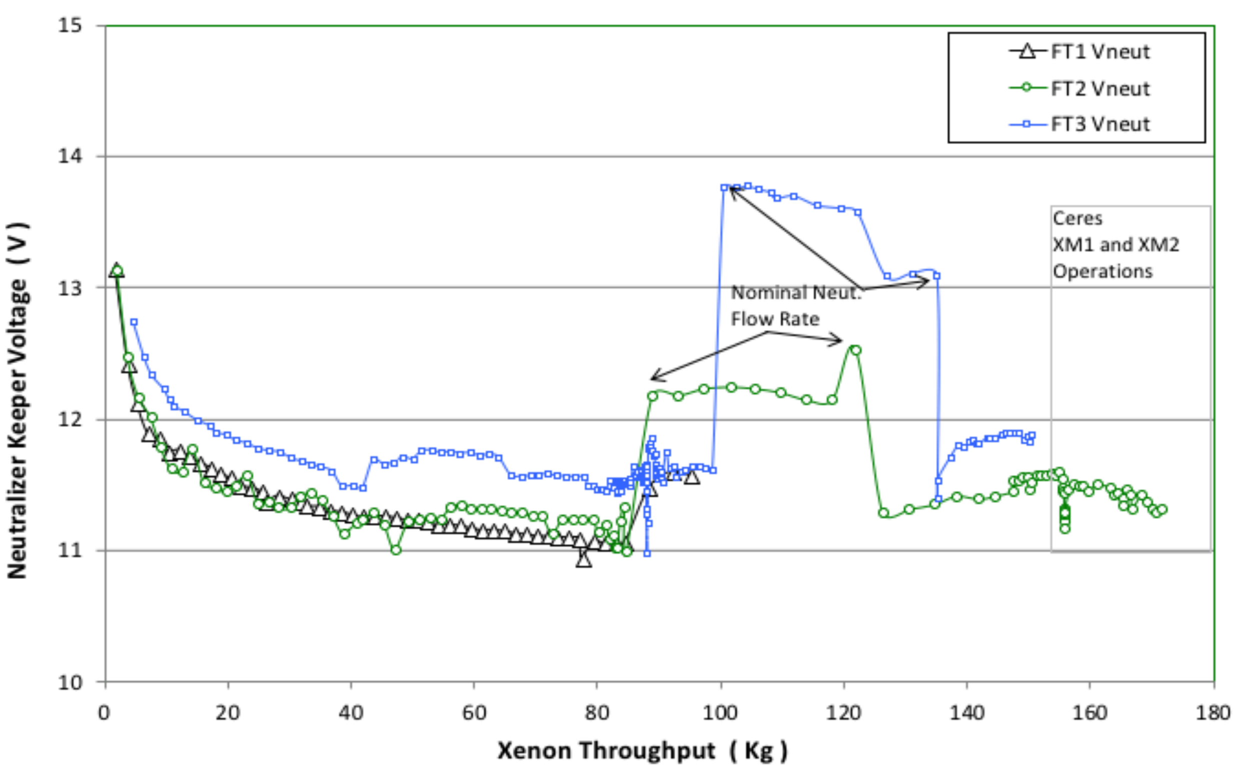


Figure 14. Dawn thruster neutralizer voltage from start of cruise to Vesta through June 2018.

**Accelerator Grid Current and Thruster Recycles**

Accelerator grid current data for Dawn ion thrusters from start of cruise to Vesta through operations at Ceres LAMO are shown in Figure 16. The accelerator grid current increased during the first 1,700 hours of operation at full power and leveled off after that. This is unlike the behavior of the accelerator grid impingement current noted in the ELT [18], which started at a higher level and then decreased over a period of approximately 1,000 hours to approximately 6.5 mA after that. Step changes in accelerator grid current are related to changes in thruster operating power and accelerator grid voltage. At a fixed flow rate and beam current thruster power can be finely controlled with step changes of approximately 10 V in beam voltage, which explains the step changes in accelerator grid current. All Dawn FTs reached end of life (EOL) xenon throughput, which is defined as reaching a total thruster throughput of 70 kg of xenon. After reaching approximately 65-75 kg of xenon throughput the accelerator grid voltage was changed for each FT, from -200 V to -272 V, to provide additional margin to electron backstreaming from thruster wear. The effect of changing the accelerator grid voltage was a slight increase in beam divergence and reduced discharge loss, caused by an increase in the grid transparency to ions. Accelerator grid impingement currents for all the thrusters were consistent with beginning of life and end of life predictions of accelerator currents made pre-launch.

Arcing or other faults can occur from grid spacing changes or from debris that bridges the gaps between the grids. The PPU is designed to clear these faults by quickly reducing discharge power, power-cycling the beam supplies, then re-establishing the discharge and beam currents to their nominal values, a process called high voltage recycling. High voltage recycles from start of cruise through June 2018 are shown in Figure 17. FT1 accumulated 67 recycles, FT2 44 recycles, and FT3 64 recycles. The data indicate that after initially increasing over a period of thousands of hours of operation, recycle rates decreased over time and with decreasing power levels. There have been very few recycles from cold starts with the thruster front masks at temperatures below -80 degrees C. Recycle rates seemed to increase on thrusters which were re-started after months or years of disuse but recycle rates were not completely consistent with thruster time spent unused.

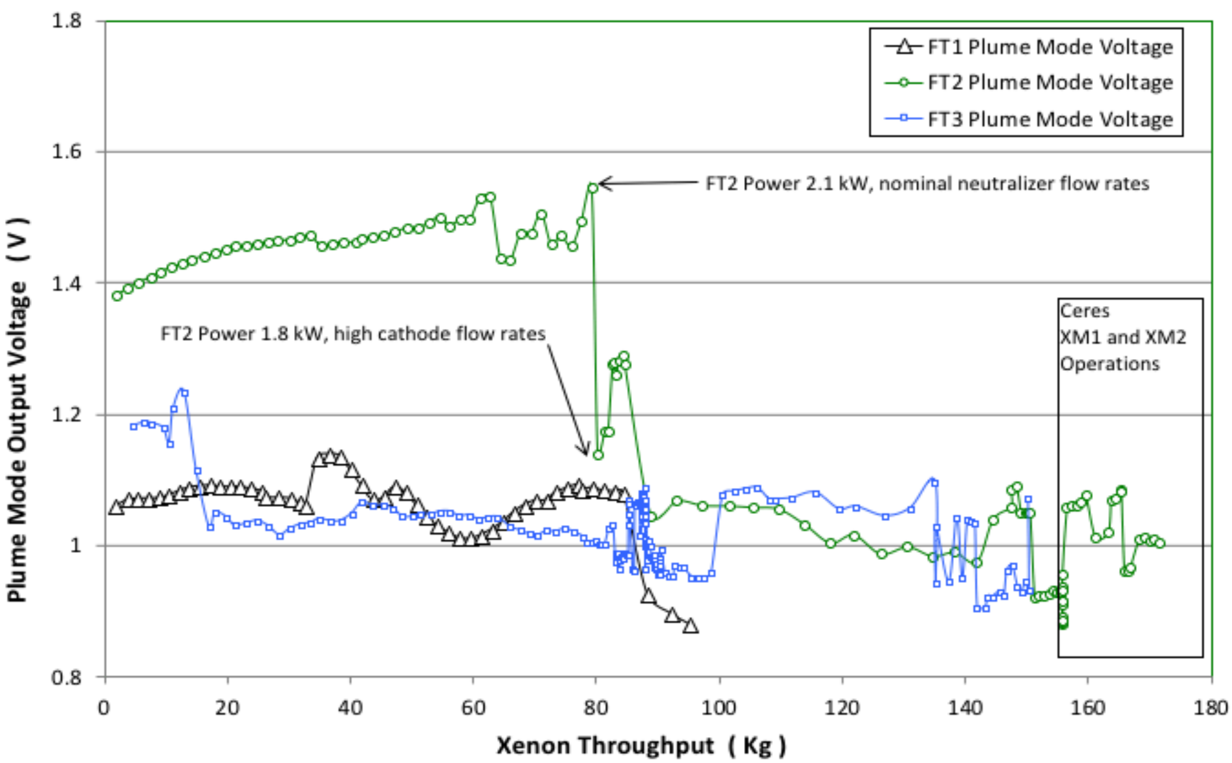


Figure 15. Dawn plume mode circuit output voltage from start of cruise to Vesta through June 2018.

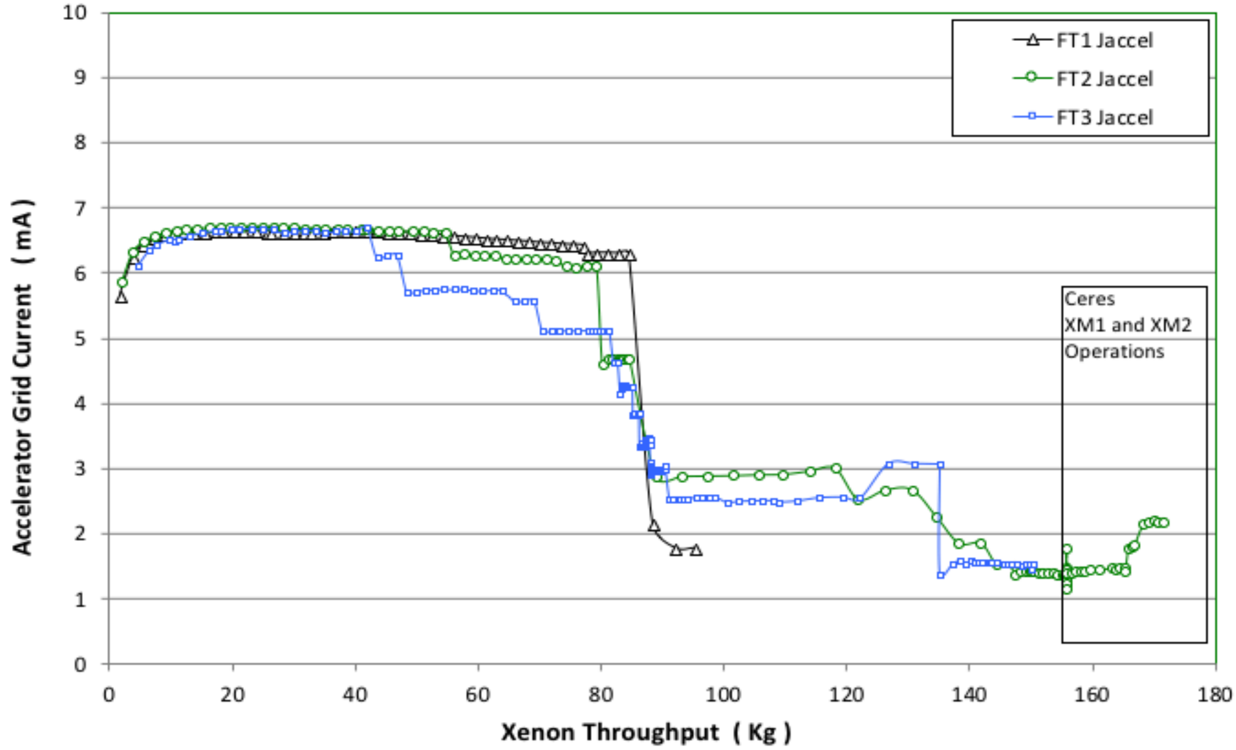


Figure 16. Dawn thruster accelerator grid current from start of cruise to Vesta through June 2018.

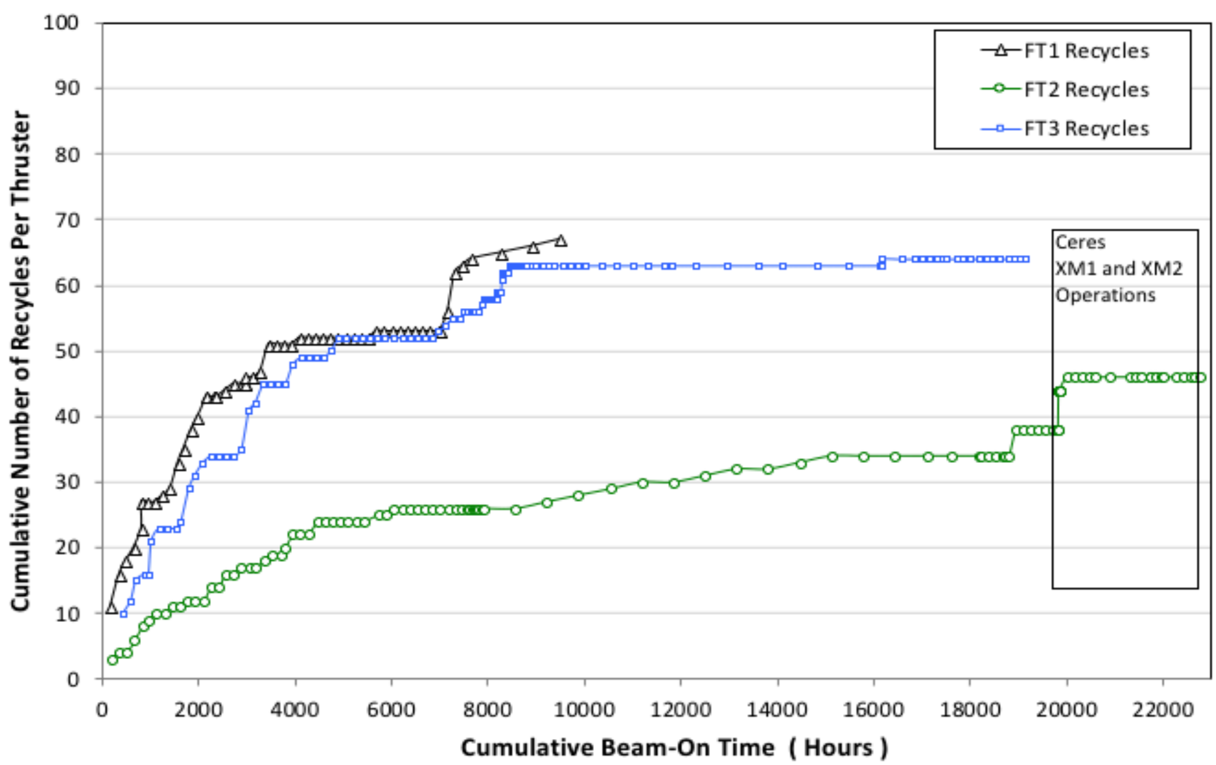


Figure 17. Dawn thruster grid recycles from start of cruise to Vesta through June 2018.

**DCIU Operation**

The DCIUs control the PPUs and the XFS, including valve control and flow rates to the engines. The DCIUs include fault protection software to turn off the power supplies and close the solenoid valves and certain latch valves if certain fault conditions are detected. The DCIUs operate at under 25 W power and generally one of the DCIUs is kept powered on because main xenon storage tank and plena tank pressure and temperature telemetry are provided by the DCIUs. Only one DCIU is powered on at any time. Since being powered on during the initial check out phase in the fall of 2007 the DCIUs have been on for approximately 90,000 hours. In that time, a period spanning almost eleven years, the DCIUs have operated almost flawlessly. All DCIU commands were accepted and executed. Three operational errors, occurring several years apart, were likely related to Dawn's space environment. One operational error, which occurred during a non-thrusting time, led to a power-on reset as designed by the DCIU's fault protection software. All these fault events were predicted as fault possibilities, plans were implemented pre-launch to accommodate them, and the IPS system and Dawn operations team were resilient to their occurrences.

The DCIU-1 faults in 2011 and again in 2014 occurred near orbit capture, the peak in sensitivity to missed thrust during the long interplanetary transfers to Vesta and Ceres. The operations team responded swiftly and productively to minimize the duration of the interruptions in thrusting, taking advantage of the flexibility provided by the IPS and the mission, with no significant consequences for science data acquisition.

## V. Conclusions

The Dawn mission successfully used its ion propulsion system for the heliocentric transfer to the main-belt protoplanet Vesta, for science operations in orbit, for departure from Vesta, cruise to the dwarf planet Ceres, Ceres approach, orbit capture at Ceres, transit to all four science orbits, and orbit maintenance maneuvers at Ceres. Dawn completed its primary mission in June 2016 and its first extended mission called XM1 in October 2017. The second extended mission, XM2, also began in October 2017. The IPS was operated for approximately 51,382 hours with beam extraction, used almost 417 kg of xenon, and imparted a delta-V of almost 11.5 km/s to the spacecraft. Dawn's final orbit at Ceres was reached on June 6, 2018, with an orbital altitude ranging between 4,000 km 35 km. This orbit is highly stable and the Dawn spacecraft will remain there for at least 20 years. Science data acquisition will continue in XM2 until the hydrazine is exhausted and attitude control is lost, which is expected to occur between August and October 2018, thus ending the mission.

The Dawn IPS has proven to be extremely reliable and capable with very few operational problems during its almost eleven-year journey. The Dawn mission will end with about 8 kg remaining of the 425 kg of xenon originally loaded, and with the ion propulsion system fully operational.

## Acknowledgments

The authors thank the many individuals at the organizations that contributed to the successful use of the IPS to enable the Dawn mission. These organizations are, in no special order: JPL, Orbital ATK, Glenn Research Center, L3, Moog, Carlton Technologies, and Starsys. This research was carried out, in part, at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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